An Exergy Analysis of the New Zealand Energy System

by

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Abstract

Exergy analysis has been shown to be a valuable method of assessing energy use on a national scale. Exergy analysis measures the work potential of mass and energy flows, and therefore more accurately identifies areas with potential for improvement. This thesis presents an exergy analysis of the New Zealand energy system. Exergy flows, from resource inputs through transformation to output end-use, are calculated and presented in Sankey diagrams. Exergy flows for the total energy system, each resource category and each sector of the economy are presented. Exergy efficiencies are calculated from these flows. Energy flows and energy efficiencies are also presented for comparison. The total exergy efficiency for NZ is 22% and energy efficiency is 38%. Results show the transportation, residential, and commercial end-use sectors have the largest exergy losses. In transportation, the losses arise from the inefficiency of the conversion of chemical fuels to motive force in internal combustion engines. In the commercial and residential sectors the losses arise from the use of high exergy sources for low temperature space and water heating. This second loss would not be captured in an energy analysis. Another significant finding is the large impact of geothermal energy resources on the analysis. Geothermal energy currently makes up 26% of NZ total primary energy resources. Energy analysis does not account for the work potential in geothermal resources used for electricity generation, and therefore over estimates the potential of the geothermal resource. Due to the large percentage of geothermal in New Zealand's energy system, this has a significant impact on overall results. Policy implications of these finding are discussed including a proposal to evaluate New Zealand's energy productivity, the ratio of economic outputs to energy inputs, based on exergy rather than energy inputs to more accurately account for geothermal resources.

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Nomenclature

Table 1. Nomenclature for energy and exergy equations

Symbol	Description	Units
E	Energy	PJ
B	Exergy	PJ
$\dot{W}$	Power	W
$\dot{B}_k$	Thermal exergy product	PJ
$\dot{Q}_k$	Thermal energy product	PJ
T_k	Process temperature	K
T_0	Environmental temperature	K
m	Mass flow	kg
b^t	Total specific exergy	kJ/kg
b^{ph}	Specific physical exergy	kJ/kg
b^{ch}	Specific non-flow chemical exergy	kJ/kg
h	Enthalpy	kJ/kg
h_0	Enthalpy at the reference state	kJ/kg
s	Entropy	kJ/kg.K
s_0	Entropy at the reference state	kJ/kg.K
KE	Kinetic energy	PJ
PE	Potential energy	PJ
B_x	Non-flow exergy	PJ
B_d	Exergy destruction	PJ
$\dot{\sigma}$	Rate of entropy generation	kJ/kg.K
Φ	Specific exergy ratio	-
[C]	Carbon atom fraction	%
[H]	Hydrogen atom fraction	%
[O]	Oxygen atom fraction	%
[N]	Nitrogen atom fraction	%
[S]	Sulphur atom fraction	%
NCV	Net calorific value	kJ/kg

GCV	Gross calorific value	kJ/kg
ψ	Exergy efficiency	%
η	Energy efficiency	%
τ	Exergetic temperature factor	-
$B_{non\text{-}heat}$	Non-heat exergy end-use product	PJ
W_e	Electricity	PJ
E_{in}	Energy input	PJ
B_{in}	Exergy input	PJ
$B_{out,useful}$	Useful exergy output	PJ
$B_{re\text{-}injected}$	Re-injected exergy	PJ
TPES	Total primary energy supply	PJ
TPExS	Total primary exergy supply	PJ

1. Introduction

1.1. Energy and Exergy Analysis

The energy systems of most countries are monitored and studied using energy analysis, which traces the quantity and allocation of primary energy resources through transformation processes to consumer energy products and end uses [1]. A national energy analysis will typically show the proportions of each primary energy resource used for each fuel resource and its allocations across each energy consuming sector. It can be a useful way of monitoring trends or changes in the way a country uses its energy resources. Energy resources can be utilised to different energy efficiencies, depending on the technologies and processes that are utilising the resources. An energy analysis can show the potential reduction in energy resource use when improvements are made to these technologies or consumption behaviours, or when changes in economic situation or fuel mix occur [1].

Energy resource can differ in “quality”, in the sense that one can do more work than another. For instance, a geothermal resource at a higher temperature can produce more work than a geothermal resource at a lower temperature in the same environment. Likewise, electricity and mechanical work are more valuable carriers than low temperature heat or energy found in a fuel. Conventional energy analysis does not consider such differences in quality of energy carriers [2].

Energy analysis is based on the First Law of Thermodynamics, which holds that energy cannot be created or destroyed, only transformed from one form to another [2]. Exergy is an alternative to energy for describing the value of a resource or the product from a conversion process. Exergy defines the quality of an energy resource based on the Second Law of Thermodynamics, which is that in any cyclic process the entropy will either increase or remain the same, where entropy is a measure of the amount of energy that is unavailable to do work [2]. The Second Law of Thermodynamics shows that not all the energy input into a system can be converted into useful work. This conversion depends on the type of energy resource, the conversion process in which it is being utilised, and the environmental conditions at which the process occurs.

Unlike energy, exergy is destroyed when a process fails to fully utilise the potential of a resource to do work. This makes exergy analysis a valuable tool for assessing the true economic and thermodynamic value of an energy resource, and where it is being inefficiently utilised in a system. Additionally, if an end-use is not well matched to the resource, the result is inefficient use of the resource [2].

By mapping the exergy changes from primary extraction and importation of energy resources to end-uses in an economy, new insights are gained into the way national energy systems utilise their resources. National exergy analyses have been carried out before in the following countries:

Table 2. National exergy analyses

Country	Year	Source
United States of America	1970	[3]
United Kingdom	1900-2000	[4]
Canada	1986	[5]
China	2003	[6]
Japan	1985	[7]
Global and OECD	1990	[8]
Norway	1995	[9]
Italy	1990	[10]
Sweden	1980	[11]
Turkey	2006	[12]
Saudi Arabia	1993-2000	[13]

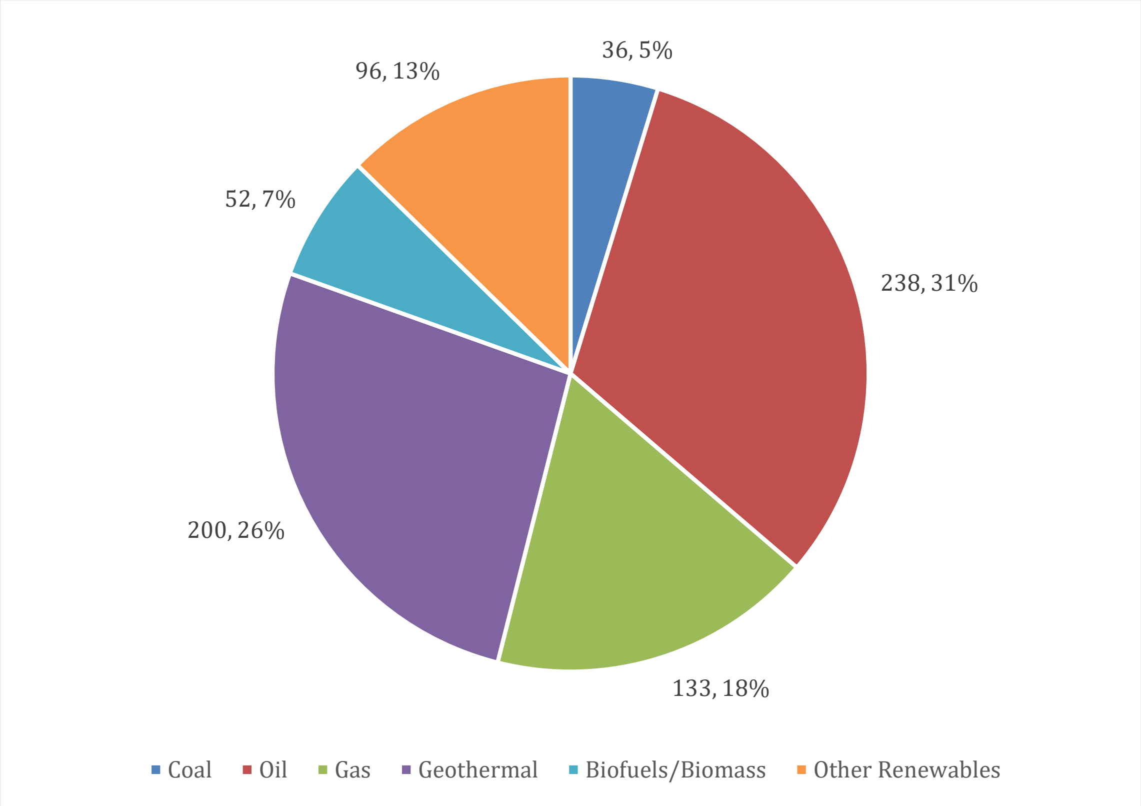
These reports have a resounding message that standard energy analysis is not able to accurately describe energy systems, and that exergy analysis is useful for capturing the true utilisation of fuels in a country. These analyses strongly support the inclusion of exergy analysis in decision making for future energy system developments and policy making activities. A trend across the results of these studies is poor exergy efficiency in transport and space heating processes, and thus they recommend more exergy efficient technologies and higher renewable energy share to reduce exergetic losses.

The objective of this thesis is to present the first exergy analysis of New Zealand's energy system, for the year 2014. Exergy flows are considered from indigenous production and importation through to conversion to useful work by end use processes and transformation processes. Key locations and causes of exergy losses are identified. The scope includes resources used for energy purposes, and does not consider material goods that are not utilised for their exergy content, i.e. the embodied exergy of goods.

1.2. The New Zealand Energy System

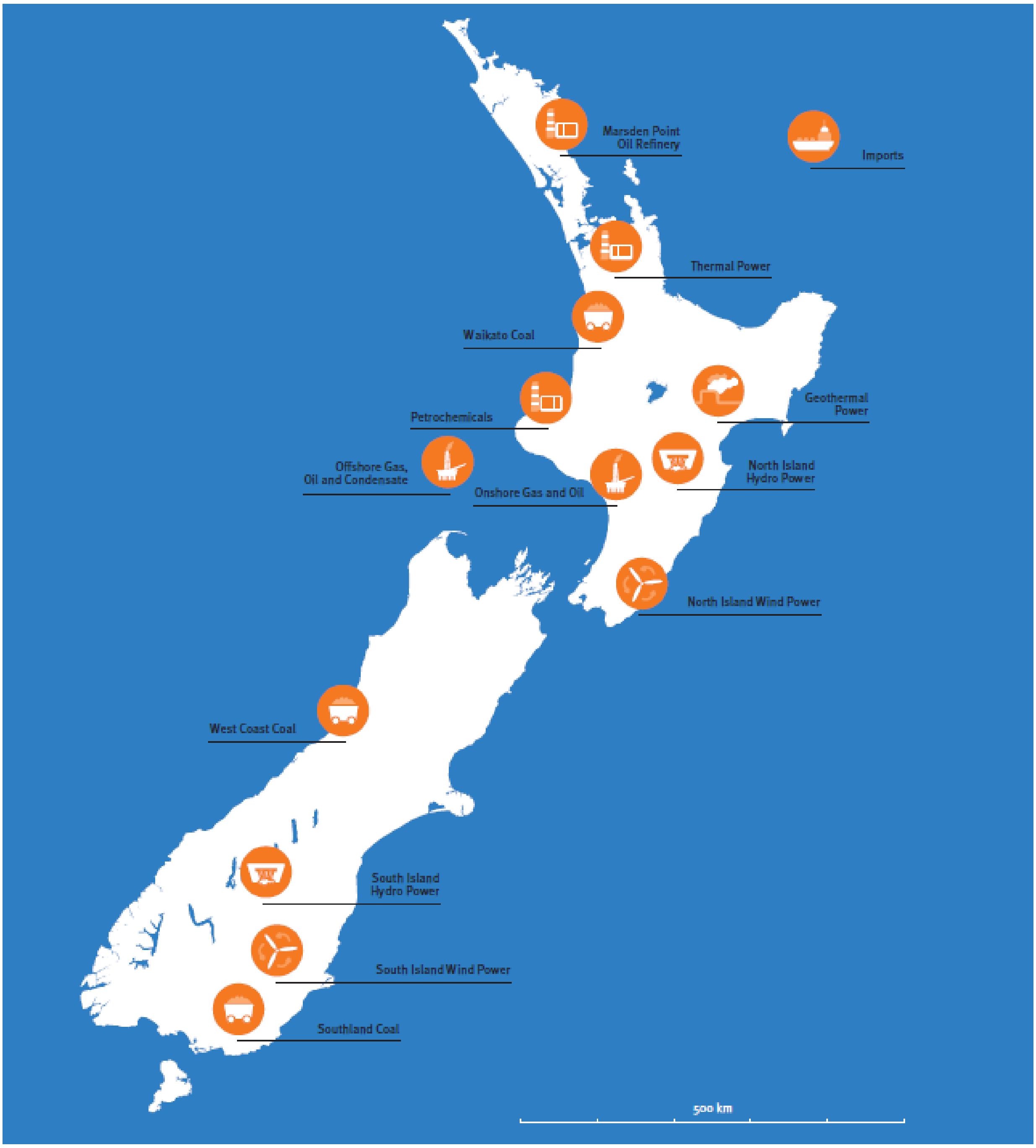
New Zealand is an island country in the south-western Pacific Ocean. It has three islands; the North Island, the South Island, and the much smaller Stewart Island. In 2014, the country's population was 4,087,500 [14]. Oil (238PJ, 31%) makes up the largest proportions of total primary energy supply (TPES) for the year 2014, shown in Figure 1 [15]. Most of the country's domestically produced crude oil is exported, and New Zealand depends on oil imports to support domestic transport. Natural gas (133PJ, 18%) and coal (36PJ, 5%) are used for electricity generation, industrial uses, and non-energy uses such as petrochemical manufacture [15]. New Zealand has for many years had a high proportion of its TPES provided by renewable resources, with well-established geothermal and hydropower systems. The proportion of geothermal energy in New Zealand's TPES (200PJ, 26%) is the second highest in the OECD [16]. In 2014, total renewable resource energy supply equalled 46% of TPES and results in New Zealand being the country with the third highest percentage of renewable energy in the OECD [17].

Figure 1. New Zealand Total Primary Energy Supply (PJ) 2014 [15]



Some resources cannot be as easily traded due to difficulties in storage and transport. New Zealand is a geographically isolated country, which means that electricity and natural gas are restricted to use within the country, and often specific locations within the country. For example, reticulated gas consumption occurs only in the North Island as this is where the gas production occurs, and there is no pipeline connection to the South Island [17]. Figure 2 below indicates locations of large scale energy resource production and processing within New Zealand. More detailed maps for each resource type can be found in "New Zealand's EnergyScape – Summary of Resource Maps" [18].

Figure 2. Major energy resource locations in New Zealand [19]

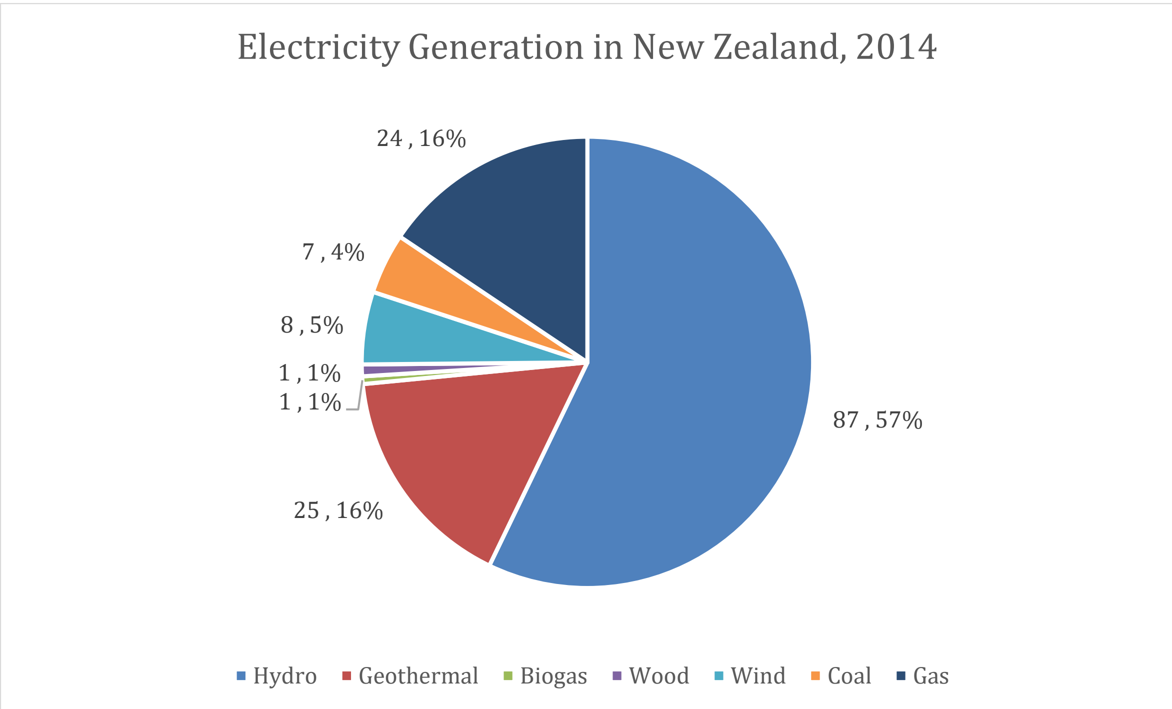


Currently, most of New Zealand's bituminous coal is exported. The bituminous coal produced in New Zealand has desirable qualities such as low sulphur and ash content, which make it valued in the international steel manufacturing market [17]. Some coal is imported to supplement fluctuations in consumption and production.

Oil and oil products are imported into New Zealand. Most of the crude oil produced in New Zealand is exported for refining as it is valued internationally due to its high quality. In 2014 only 3% of nationally produced crude oil was refined at the Marsden Point Refinery, which is designed to utilise light crude [17].

Electricity generation is dominated by hydro and geothermal power stations, which together supplied 73% (112PJ) of New Zealand's electricity demand in 2014. Natural gas is consumed to provide the next highest proportion of electricity generation (24PJ, 16%), followed by wind (8PJ, 5%) and coal (7PJ, 4%). Small amounts of electricity are generated from biogas, woody biomass, which can be seen in Figure 3, as well as oil, solar PV and waste heat, but these are such small proportions of total generation that they do not appear on the figure. Electricity is distributed through the national grid for nationwide use in all sectors.

Figure 3. Electricity generation from sources in New Zealand (PJ), 2014 [15]



A list of locations of resource production, major use, imports and exports for New Zealand can be found in Appendix A.1. Many of these sites are important to this project as they are the major producers and consumers of energy resources in New Zealand.

1.3. New Zealand Exergy Studies

A number of exergy studies have previously been carried out in New Zealand, however this thesis represents the first national-level exergy analysis of New Zealand's energy system. Previous studies range from analysis of the dairy industry [20], technical analysis of aspects of geothermal power plants [21], [22], and the integration of geothermal heat in biochemical lignocellulosic biorefineries [23]. Two key studies that apply directly to this New Zealand exergy study include the analysis of the Wairakei [24] and Poihipi Road [25] geothermal power stations. These studies look at the flows of mass, energy and exergy from the geothermal reservoir, through the geothermal power stations, and on to any further users. Water rejection, reinjection, and disposal are analysed, as well as losses to the air and from steam transport pipes. These studies provide a good basis for the methodology for exergy analysis of geothermal systems. They provide energy and exergy values for two geothermal power stations in New Zealand, which can be used for comparison to the results from geothermal systems in this national exergy analysis.

1.4. Data Resources

The scale and scope of this thesis mean that direct data measurements were an impractical source of data, so existing recognised data collections were used. The accuracy of the results depended on the quality and quantity of the data, and appropriate assumptions were made where data was lacking. Three major databases are used: Ministry of Business, Innovation and Employment (MBIE) Data Tables [15], Energy Efficiency and Conservation Authority (EECA) End-Use Database [26], and the 2014 Geothermal Direct Use Database [27]. These three sources of data cover most the data required for this project, but additional sources of data are required for areas where more or more specific data is required. These additional data sources are described within the methodology of the appropriate resource chapters.

This thesis utilises data from a variety of resources, and it is important to use a common convention for classifying this data. The Australian and New Zealand Standard Industrial Classification (ANZSIC) codes are used to organise end uses into the appropriate sector. A table of these classifications is included in Appendix A.2. The definitions of these classifications, as well as other categories such as end use processes, are included in Appendix A.3.

1.4.1. MBIE Data Tables

MBIE produce their data tables annually, and provide them for public use on their website [15]. These data tables provide information on the energy resources available in New Zealand in terms of mass and energy flows through New Zealand. Data is available for each fuel resource in New Zealand, including the quantity of fuel produced, imported, exported, consumed, and transformed. Data is broken down into sub-categories of fuel types, for example coal is divided into bituminous, sub-bituminous, and lignite. Fuel properties of resources from different location in New Zealand are also included. This data forms the basis for much of the New Zealand exergy analysis and the available mass and energy flows within the country. Exergy values are calculated from the mass flow and composition data under standard conditions.

1.4.2. EECA End Use Database

The EECA Energy End-Use Database [26] includes valuable information on where and how energy is used in New Zealand. The data is presented in an online tool [26], which can be downloaded in excel format. It includes energy flows to end use sectors, technologies, and processes for the years 2012, 2013 and 2014. This data helps to understand the flows of energy to different end uses. The proportions of energy delivered to each end use are used to determine exergy proportions to each end use technology and process. This is discussed in the General Methodology section of this thesis.

Data in the database is presented in the form of "delivered energy" (the energy input) and "end-use energy" (the energy product). These two energy values are used to calculate the efficiencies of the individual end-use processes. Exergy efficiencies for heat end-use processes are calculated from these efficiencies, a process that is explained in full in section 2.6.3.

1.4.3. Geothermal Database

While the MBIE database does include large amounts of information for resource flows throughout New Zealand for coal, oil and natural gas, there is little information included for geothermal resources. The New Zealand Geothermal Association produces an annual report that includes data on direct geothermal use in New Zealand [27]. This database includes information on the energy of the geothermal resource that is delivered to end-use processes, and is the basis for the exergy analysis of geothermal direct use in this thesis.

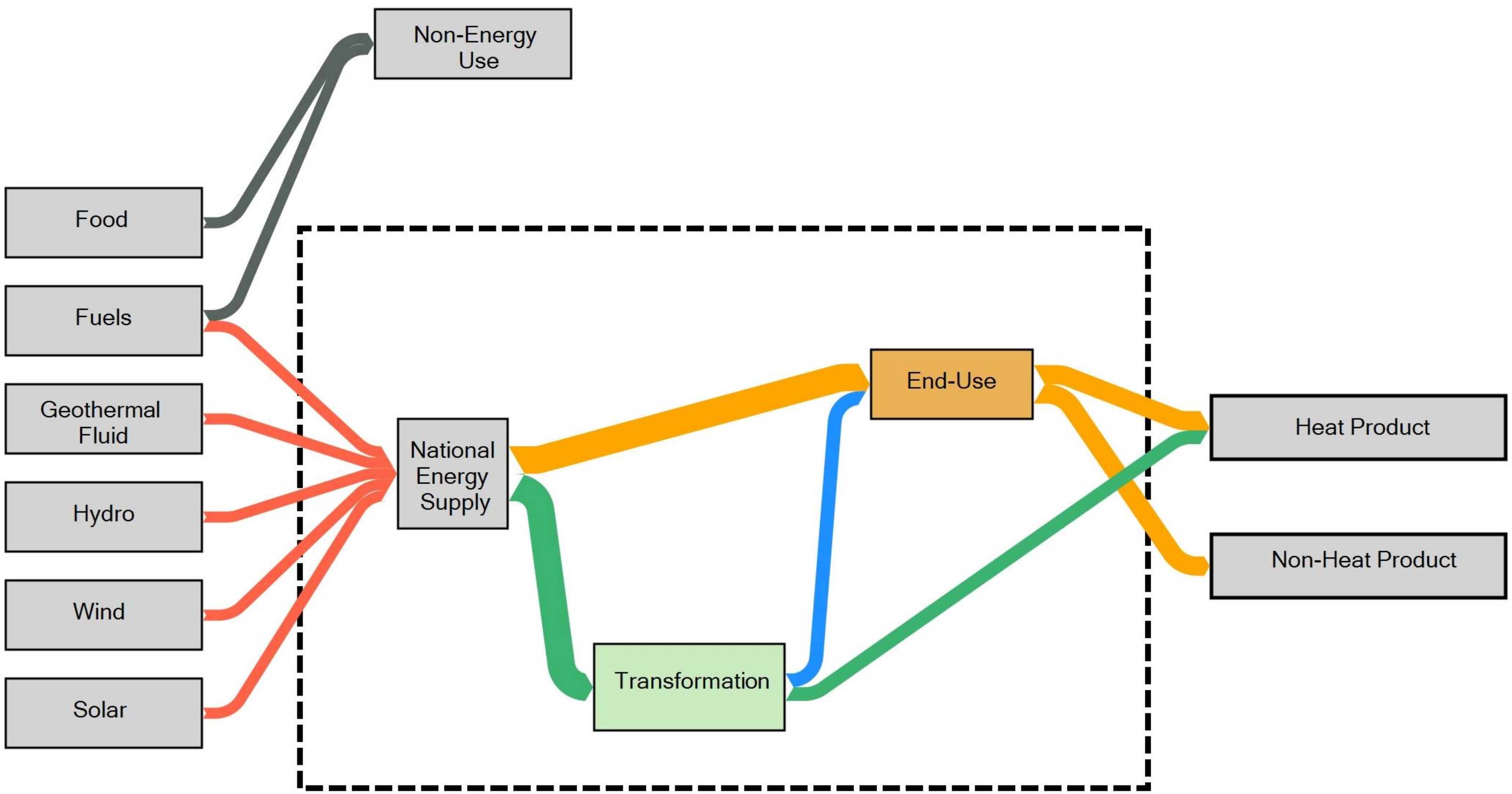
2. General Methodology

This section outlines the specific system being studies, the scope of analysis and the general methodology for calculating exergy flows through the New Zealand energy system. This general methodology is intended to outline the analytical process used for the specific requirements and limitations of each fuel type.

2.1. System Flows

The New Zealand energy system is a complex web of interactions between energy and material flows. The boundaries between these flows are often ill-defined. For the purpose of this thesis we have developed a definition of the New Zealand energy system in terms of energy inputs and outputs to the system. This definition of the system in terms of its inputs and outputs is depicted in Figure 4.

Figure 4. Inputs to and outputs from the defined system boundaries for New Zealand.



A description of the inputs and outputs to the New Zealand energy system are given below.

Inputs:

- Fuels: Coal, oil, natural gas, biogas and biomass. These resources are utilised for their chemical components.
- Geothermal fluid: Geothermal fluid is utilised in geothermal power stations, and also in secondary and direct use purposes.
- Hydro and wind carry out mechanical work on turbines to generate electricity.
- Solar is used for electricity generation and for direct water heating.

Non-Energy Use:

- Some studies [6] [7] [9] include the energy and exergy embodied in food, crops and other products in their analysis, but these are not included in this current study.
- Some fuels are used for purposes other than energy sources, such as natural gas used to produce fertiliser, or coal which is used as a reductant in the steel manufacturing process. These are not defined as an energy resource in the MBIE data sets [15], so they are not included in the current exergy analysis.

Transformation:

- Electricity: Power stations and cogenerations site produce electricity from the range of inputs listed above. Electricity is also delivered to end-use processes as an input. Electricity is pure exergy, in the sense that it can be transformed into work with 100% efficiency. Therefore, the exergy value of an electricity flow is equal to its energy value [28].

- Cogeneration: Some industrial sites that use fuels for heat processes also generate electricity from waste heat products, or utilise the waste heat from electricity generating processes. Energy and exergy products from these sites are both the heat created for the industrial process and the electricity that is generated.
- Waste heat output from exothermic processes is used to generate electricity.

Outputs:

- Heat Products: This applies to end-use processes such as space and water heating, as well as the heat product from cogeneration systems. There is a heat transfer from the energy system into the end use, and it is the exergy of this heat flow that is considered the exergy product.
- Non-Heat Products: Includes mechanical work such as transport, motive power, and pumping systems. This also includes other end-uses such as lighting and electronics which do not fit into heat or mechanical work end-use categories.

2.2. Exergy

Exergy is the maximum theoretical work obtainable from a system and the surrounding environment as the system comes into equilibrium with the environment (passes into the dead state). Therefore the exergy of a system is defined with respect to a reference environment. When the system is in complete thermodynamic equilibrium with the environment, the system is said to be in a dead state. This means a material stream at equilibrium with the dead state will have zero exergy. A system can be in restricted equilibrium with its environment, i.e thermal and mechanical equilibrium only, but not chemical equilibrium. In this case, exergy is non-zero, and this is the chemical exergy of the material stream. Chemical exergy of such a stream is determined by its temperature, pressure, and its chemical compositions and those of the environment. In this study the exergy reference environment from Szargut, Morris and Steward with temperature 25°C and pressure 1atm has been adopted [2].

Exergy analysis is carried out by dividing the total system into a number of subsystems. The exergy flows into and out of each subsystem are given by [29]:

<u>Equation 1:</u>

$$\underbrace{\frac{dB_x}{dt}}_{\substack{Accumulation\ of\\ non-flow\ exergy}} = \underbrace{\sum_{j}^{n_W} \dot{W}_j}_{\substack{Exergy\ transfer\\ through\ work}} + \underbrace{\sum_{k}^{n_Q} \dot{B}_k^Q}_{\substack{Exergy\ transfer\\ through\ heat}} \underbrace{\sum_{i}^{n_{in}} \dot{m}_i^{in} b_i^t}_{\substack{Flow\ exergy\\ into\ system}} - \underbrace{\sum_{e}^{n_{out}} \dot{m}_e^{out} b_e^t}_{\substack{Flow\ exergy\\ out\ of\ system}} + \underbrace{\dot{B}_d}_{\substack{Exergy\\ destruction}}$$

Each term in Equation 1 is described below.

Work transfer:
Work (which can be mechanical or electrical) is equal to its exergy [2]. The net exergy flow is obtained by the summing of all work transfer into and out of the system.

Heat transfer:
Heat is one possible output or product from the system. The exergy of heat flow ($\dot{B}^Q$) is given by [2]

<u>Equation 2:</u>

$$\dot{B}_k^Q = \dot{Q}_k \left(1 - \frac{T_k}{T_0}\right)$$

where $\dot{Q}_k$ is the heat flow through surface area element k. T_k is the temperature of the heat flow and T_0 is the environment temperature, both in Kelvin.

Input and output of flow exergy via mass flows:
The exergy of each component of the input and output mass flows are given by the product of the mass flow and the specific exergy.

Equation 3:

$$B_i = b_i^t \times m_i$$

The specific exergy of each component is the sum of physical exergy and non-flow chemical exergy.

Equation 4:

$$b^t = \underbrace{b^{ph}}_{Physical\ exergy} + \underbrace{b^{ch}}_{Non-flow\ chemical\ exergy}$$

Physical exergy considers enthalpy and entropy of the resource, as well as the kinetic and potential exergy, shown in Equation 5.

Equation 5:

$$b^{ph} = h - h_0 - T_0(s - s_0) + KE + PE$$

Kinetic (KE) and potential (PE) exergies are presumed to equal zero in this analysis [29]. Non-flow chemical exergy is calculated from chemical compositions of the fuel. This is explained in detail in the section “2.3. Fuels”.

Accumulation of non-flow exergy:

In the steady state conditions under consideration here we assume that there is no accumulation of non-flow exergy [29]:

Equation 6:

$$\frac{dB}{dt} = 0$$

Exergy Destruction:

Exergy destruction is related to the entropy generation within the system through the Gouy-Stodola theorem [2]:

Equation 7:

$$\dot{B_d} = T_0\dot{\sigma}.$$

Here, $\dot{\sigma}$ is rate of entropy generation and T_0 is environment temperature.

Exergy loss:

In this thesis, exergy conversion loss for a subsystem is determined by the difference between the total exergy inputs and the total exergy of the useful products from a subsystem [28]:

Equation 8:

$$Exergy\ conversion\ loss = B_{in} - B_{out,useful}$$

The exergy loss thus includes both exergy destruction due to irreversibilities and unutilised outputs (or waste products)

Equation 9:

$$Exergy\ conversion\ loss = \dot{B}_d + \sum_{\substack{waste\ exit\\ streams}} \dot{m}_w b_w^t$$

2.3. Fuels

Fuels include coal, oil, natural gas, biogas and biomass. Fuels are presumed to be at thermal and mechanical equilibrium with the environment, such that $b^{ph} = 0$ in Equation 5. The exergy of fuels is calculated as the product of mass flows and specific exergy values, which are derived from their chemical exergy, as explained below.

2.3.1. Composition Data

The specific exergy depends on the chemical composition and the environmental conditions. Composition data for each fuel is found in terms of ultimate analysis; mass fractions of carbon, hydrogen, oxygen, nitrogen and sulphur. Each fuel is categorised to the finest level of composition data available. Table 3 shows the final composition values used in this thesis.

Table 3. Final resource mass fractions (%) from ultimate analysis

Resource	Bituminous Coal [30]	Subbituminous Coal [30]	Lignite Coal [30]	Oil [31]	Natural Gas [31]
Carbon	76.9	75.1	67.8	84	25.3
Hydrogen	5.3	5.2	4.9	15	56.6
Oxygen	15.6	18.2	25.6	0	18
Nitrogen	1.1	1.1	0.9	0	0
Sulphur	1.1	0.3	0.8	1	00.1

Compositions used for biofuels, including biogas, woody biomass and black liquor can be seen in section 7.2.1.

2.3.2. Specific Exergy

Specific exergy, the exergy per unit mass, is determined for each fuel type. Exergy flows can be found by multiplying the specific exergy by mass flows of a fuel.

For many fuels, it has been found that the fuels chemical exergy is proportional to its net calorific value (NCV), such that:

Equation 10:

$$b_{ch} = \phi \times \text{NCV}$$

where ϕ is a proportionality constant [31].

Empirical equations and relationships exist that relate chemical composition data to ϕ [31]. This enables us to use Equation 10 to calculate the specific chemical exergy of each fuel using the determined ϕ values and NCV.

Solid, liquid and gaseous fuels have different empirical equations for ϕ. The chemical compositions that were used for this project are shown in Table 3. A ϕ value is calculated for each resource type using chemical composition data and the empirically determined equations shown in Table 4.

For each of these equations, [H]/[C], [O]/[C], [N]/[C], [S]/[C] are the atomic ratio of the elements, and N_C is the mean number of carbon atoms in the molecule.

Table 4. Equations for calculating ϕ ratio [31]

Solid Fuels	Condition
Equation 11: $$\phi_s = 1.0437 + 0.0140\frac{[\mathrm{H}]}{[\mathrm{C}]} + 0.0968\frac{[\mathrm{O}]}{[\mathrm{C}]} + 0.0467\frac{[\mathrm{N}]}{[\mathrm{C}]}$$	when [O]/[C]≤0.5
Equation 12: $$\phi_s = \frac{1.044 + 0.0160\frac{[\mathrm{H}]}{[\mathrm{C}]} + 0.3493\frac{[\mathrm{O}]}{[\mathrm{C}]} + \left(1 + 0.0531\frac{[\mathrm{H}]}{[\mathrm{C}]}\right) + 0.0493\frac{[\mathrm{N}]}{[\mathrm{C}]}}{1 - 0.4124\frac{[\mathrm{O}]}{[\mathrm{C}]}}$$	when [O]/[C]≤2
For solid fuels that contain sulphur:	
Equation 13: $$b_{ch,0} = \phi_s(\mathrm{NCV}) + 6740[\mathrm{S}]$$	
Liquid Fuels	
Equation 14: $$\phi_l = 1.0407 + 0.0154\frac{[\mathrm{H}]}{[\mathrm{C}]} + 0.0562\frac{[\mathrm{O}]}{[\mathrm{C}]} + 0.5904\frac{[\mathrm{S}]}{[\mathrm{C}]}\left(1 - 0.175\frac{[\mathrm{H}]}{[\mathrm{C}]}\right)$$	
Gaseous Fuels	
Equation 15: $$\phi_g = 1.0334 + 0.0183\frac{[\mathrm{H}]}{[\mathrm{C}]} - 0.0694\frac{1}{N_C}$$	

It is important to note here that Equation 11 is used for coal calculations because [O]/[C] is <0.5, for all coal compositions used in this analysis. The ϕ values for each fuel type can be seen in Table 5 below.

Table 5. ϕ values for calculating specific exergies

Resource	Fuel Phase	ϕ value
Bituminous Coal	Solid	1.06
Subbituminous Coal	Solid	1.06
Lignite Coal	Solid	1.07
Oil	Liquid	1.07
Natural Gas	Gaseous	1.04
Biogas	Gaseous	1.04
Woody Biomass	Solid	1.12
Black Liquor	Liquid	0.92

2.4. Geothermal

The input and output flows of geothermal fluid are calculated from the product of mass flows and specific exergy values. It is assumed that the chemical exergy proportion of total exergy of geothermal fluid is negligible when compared to the physical exergy component [23]. The specific exergy of geothermal fluid is calculated from the specific enthalpy and entropy via Equation 5. Specific enthalpy and specific entropy values are determined by approximating the geothermal fluid as water and using the NIST Reference Fluid Thermodynamic and Transport Properties Database [32]. Fluid from the reservoir is approximated as a saturated liquid when sufficient data is unavailable. Specific exergies are calculated for each stage of fluid flow through the geothermal system.

Temperature and pressure data are collected for four stages of fluid flow through the control volume:

- input geothermal fluid data from the reservoir,
- product fluid data for secondary and direct use,
- outlet fluid data to be re-injected,
- waste outlet fluid data that is rejected.

Specific exergy values are multiplied by mass flow data to determine total exergy flows entering and exiting the subsystems. Exergy products were calculated for secondary and direct use from the fluid temperature and pressure data. This method combines the exergy destruction and exergy losses for the secondary and direct uses. Re-injected fluid is the part of the original resource which was not fully consumed, and the work potential of this fluid can be reused after reinjection, so it is not included as part of the waste products and losses.

Temperature and pressure data for geothermal power plants are sourced from various resources that can be seen in Table 30. Temperature and pressure data for secondary use and direct use are provided by in the 2014 Geothermal Direct Use Database [33]. In some cases, energy and exergy analyses have already been carried out on a power plant, and the results from these analyses were used directly. These include Wairakei [24]and Poihipi Road [25].

Geothermal steam quality varies considerably from site to site, and there is no consistent or representative geothermal steam quality data. Data was obtained from multiple sources in an attempt to seek detailed data for each geothermal site. Approximations and assumptions have had to be used, and these have been noted where applicable. It is important to note that, as result of the inconsistencies in the data, the results are indicative of an average geothermal energy system.

2.5. Other Renewables

A number of renewable resources, including hydropower, wind and solar PV, require a different method for analysis. Hydropower converts potential energy to usable electricity, wind converts kinetic energy to usable electricity, and solar converts radiation energy to electricity or heat. These renewable resources do not have a fixed input resource availability, instead the resource is limited by the technology in place to capture the renewable energy. To treat these resources in our analysis, we make the simplifying assumption that the exergy input is equal to the energy input as the wind, hydro and solar PV all generate electricity from work inputs. Energy and electricity data are sourced from the "Electricity" and "Renewables" MBIE data tables [15].

Data on solar thermal delivered and end-use energy is included in the EECA End-Use Database [26], and the heat product is assessed in the same way as other heat end-use processes, which is discussed in section 2.6.3.

2.6. Exergy Conversion Processes

Energy resources are utilised in a variety of different processes. In this thesis, these processes are divided into transformation and end-use processes. Transformation processes include electricity generation, cogeneration and other transformation, and are based on MBIE data [15]. Other transformation is coal that is used in the iron and steel production process as a carbon source. As this coal is not used as an energy resource, it is not included in the current exergy analysis.

End-use processes are divided into heat and non-heat processes, depending on the energy product. The methods used for exergy analysis of conversion processes are described in sections 2.6.3. and 2.6.4. below.

2.6.1. Delivered Exergy

First, the exergy of the resource that is delivered to each conversion process is calculated. Transformation processes are based on MBIE data, which is supplied in terms of delivered mass and energy. For these processes, the delivered exergy is calculated using Equation 3.

The analysis of end-use processes is based on EECA End-Use Database data [26] as well as MBIE data [15]. Total exergy delivered to each end-use sector is calculated from MBIE mass data using Equation 3. The EECA end-use database supplies delivered energy data for the individual end-use processes within these sectors. This data is in terms of energy, and not mass flows. MBIE provide mass data for total sector end-use consumption, so total delivered exergy to each sector is calculated. Exergy inputs to each end-use process are calculated from the proportions of delivered energy. The total delivered exergy to each end-use sector is divided between each end-use process within that sector according these proportions. This process provides a practical approach to approximating the exergy flows delivered to end-use processes, considering the available data.

The following sections describe how the exergy products of the conversion processes are calculated.

2.6.2. Electricity Generation

Exergy flows were calculated by carrying out an exergy balance for each transformation category applicable to the resource. The exergy input was determined from specific exergy and mass input data, described in section 2.6.1. The exergy product was the total electricity produced from the resource. Electricity data was sourced from the Electricity Authority's online tool [34] and MBIE data tables [15].

2.6.3. Heat End-Use

The exergy of heat end-use processes is calculated using Equation 2. We can write this as:

Equation 16:

$$B^Q = Q \times \tau$$

Equation 17:

$$\tau = 1 - \frac{T_0}{T}$$

Exergy products for thermal processes are calculated using Equations 16 and 17 and the temperature data in Table 6 below. The sources of this temperature data are included in the table. These sources were used to choose a temperature value for the analysis. The EECA End-Use Database includes temperature ranges for heat products, which agree with the temperature values that were chosen here.

Table 6. Process and environmental temperatures for end-use calculations

End Use Process	Environmental Temperature (°C)	Process Temperature (°C)	References	Exergetic Temperature Factor
Al_2O_3 Reduction	12.4	960	[35]	0.77
Fe_3O_4 Reduction	12.4	950	[35]	0.77
High Temperature Process Heat	12.4	494	[28]	0.63
Intermediate Temperature Cooking	12.4	121	[3]	0.28
Intermediate Temperature Process Heat	12.4	227	[28]	0.43
Low Temperature Clothes Drying	12.4	77	[3]	0.18
Low Temperature Process Heat	12.4	57	[28]	0.14
Low Temperature Space Heating	9.8	17.3	[36]	0.02
Low Temperature Water Heating	12.4	60	[37]	0.14
Refrigeration	12.4	-4.3	[3]	-0.06
Space Cooling	17.3	16	[3]	0.01

The decision was made to calculate environmental temperatures for each end-use process so that there were appropriate temperature differentials between process and environmental temperature. For example, if the environmental temperature for space heating were to be the standard 25°C, space heating could not occur to produce a temperature of 17.3°C. This methodology introduces some inconsistencies with the calculation of specific exergy values of energy resources, but the difference is much smaller that the error introduced by setting a standard environmental temperature of 25°C. In future works, individual specific exergies of the resource at each environmental temperature could be calculated. Environmental temperatures were based on NIWA monthly national temperature data [38], which can be seen in Appendix A.5. The average annual temperature for 2014 is used for all processes except for space heating and cooling.

The BRANZ HEEP study [36] found that the average building temperature was 17.3°C. For the purpose of this work, we assume that space heating occurs when the temperature is below 17.3°C, and space cooling occurs when the temperature is above 17.3°C. Average cooling temperature is calculated as the average temperature when the temperature is above 17.3°C. Average heating temperature is calculated as the average temperature when the temperature is below 17.3°C.

The exergy products are calculated from the exergetic temperature factors in Table 6 and the energy products from each end-use process [26] using Equation 16.

Note that this method of determining the exergy of heat end uses assumes that heat is the only product of value. Lack of data on end use processes constrained us to using this approach. A similar approach has been used by other authors [2] [3] [28]. Note that this also enables us to compare our results with these other studies.

2.6.4. Non-Heat End-Use

End-use processes that create non-heat products include lighting, electronics and other electrical uses, motive power, transport and pumping. For these processes, exergy of the end-use product was determined from the exergy input to the end-use and average process exergy efficiencies recorded in the literature.

Given an exergy efficiency of ψ, the exergy of the end-use product is given by:

<u>Equation 18:</u>

$$B_{non-heat} = B_{in} \times \psi$$

The average exergy efficiencies (ψ) of the end-use processes considered here, and their corresponding energy efficiencies (η), are given in Table 7.

Table 7. Energy and exergy efficiencies of end-use processes [39]

Process	Energy efficiency (%)	Exergy efficiency (%)	Description
Diesel engine	22	21	Compression ignition diesel engine: truck, car, ship, train, generator
Petrol engine	13	12	Spark ignition otto engine: car, generator, garden machinery
Aircraft engine	28	27	Turbofan, turboprop engine
Other engine	47	25	Steam or natural gas powered engine
Electric motor	60	56	AC/DC induction motor (excl. refrigeration)
Oil burner	61	15	Oil combustion device: boiler, petrochemical cracker, chemical reactor
Biomass burner	34	7	Wood/biomass combustion device: open fire/stove, boiler
Gas burner	64	13	Gas combustion device: open fire/stove, boiler, chemical reactor
Coal burner	59	19	Coal combustion device: open fire/stove, boiler, chemical reactor
Electric heater	80	24	Electric resistance heater, electric arc furnace
Heat exchanger	87	24	Direct heat application: district heat, heat from CHP
Heat pumps	COP 3.4	72	Source: [28]
Cooler	104	7	Refrigeration, air con.: industry, commercial, residential
Light device	13	12	Lighting: tungsten, fluorescent, halogen
Electronic	20	6	Computers, televisions, portable devices

2.6.5. Cogeneration

Cogeneration is treated as a combination of an end-use process and a transformation process. The total system product is the sum of electricity and heat products. Electricity data was sourced from the Electricity Authority [40], and heat products were calculated by the method described in section "2.6.3. Heat End-Use". The heat product is calculated from energy efficiency of the cogeneration technology (η) and the total energy input, assuming energy conservation. To determine the exergy content of this heat product, the heat product is multiplied by an exergetic temperature factor via Equation 16. The exergetic temperature factor is determined from temperature data of each cogeneration system, which is shown in the corresponding resource chapters. The overall relationship for calculating heat product from a cogeneration system is given by:

Equation 19:

$$B^{Q} = (\eta \times E_{in}) \times \tau$$

The exergy of the heat product is added to the electricity generated to find the total exergy product. A full list of cogeneration plants in included in Appendix A.4.

2.7. Efficiencies

The results of exergy analysis are often presented in terms of efficiencies. Energy efficiency (η) of a system is defined as the usable energy output over the total energy input to the system:

Equation 20:

$$\eta = \frac{Usable\ energy\ output}{Total\ energy\ input}$$

Exergy efficiency (ψ) is calculated by comparing the actual work output to the maximum potential work output of the energy resource, shown below in Equation 21. It describes how well an end-use process can capture the potential of an energy resource to do work [39].

<u>Equation 21:</u>

$$\psi = \frac{Actual\ work\ output}{Maximum\ possible\ work\ output}$$

Cogeneration systems have both an electricity product and a heat product. Energy efficiency of a cogeneration system is calculated from the total energy input (E_{in}) and the sum of the energy of the electricity product (W_e) and the energy of the heat product (E_{in}), shown in Equation 22.

<u>Equation 22:</u>

$$\eta_{cogen} = \frac{W_e + \sum Q}{E_{in}}$$

Exergy efficiency of a cogeneration system is calculated from the total exergy input (B_{in}) and the sum of the exergy of the electricity product (W_e) and the exergy of the heat product (B_{th}), shown in Equation 23.

<u>Equation 23:</u>

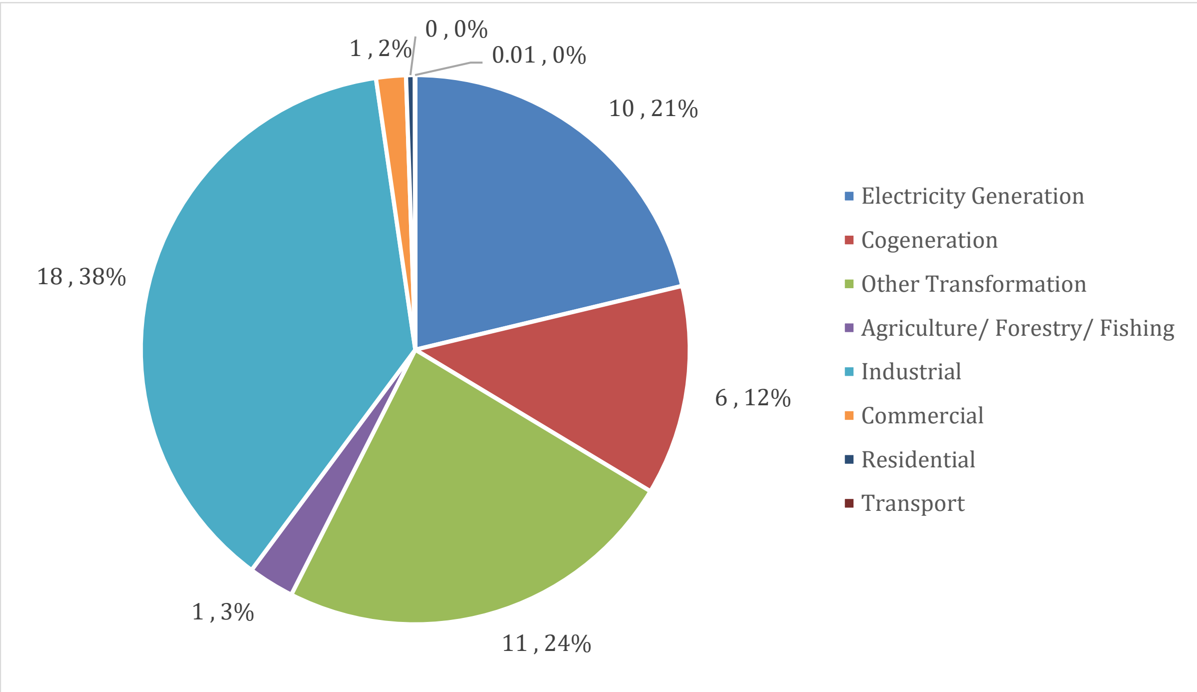
$$\psi_{cogen} = \frac{W_e + \sum B^Q}{B_{in}}$$

3. Coal

3.1. Coal Use in New Zealand

A significant indigenous resource in the early 20th century, coal is no longer a major energy resource in New Zealand, supplying only 5% (38PJ) of New Zealand's TPES in 2014 [15]. Electricity generation, steel production, and industrial processes are the major coal consumers in New Zealand.

Figure 5. Delivered Coal Energy to End Uses and Transformation Processes, 2015 [15]



The 1000MW Huntly Power Station located in the Waikato region of the North Island is the only coal-fired power station in New Zealand. It utilises 21% (10PJ) of the total coal consumption in New Zealand [17]. The four 250MW dual fuel coal/gas modified-Rankine cycle units are likely to be all retired by 2021 [41]. The second of the boiler turbine units was retired in June 2015 [42], with the remaining two boiler-turbine sets expected to be retired by December 2018 [43].

Most of New Zealand's coal supply comes from indigenous production, but some coal is imported to supplement coal requirements that are not met by indigenous production [19]. Some bituminous coal is used for cement production and other end uses, but most of New Zealand's bituminous coal is exported, mainly to India and Japan. Exported coal is generally high quality bituminous coal for steel reduction or as a feedstock for chemical processes [17] and is excluded from this analysis as its consumption occurs outside the study's boundary of the New Zealand energy system.

The NZ Steel mill, located near Auckland uses 36% (17PJ) of New Zealand's coal supply, which is defined as a combination of the coal delivered to cogeneration and other transformation [17]. This site utilises coal for multiple purposes; as a source of carbon for iron ore reduction, as an energy resource to provide heat to the steel production process, and also generating electricity by utilising waste heat from steel production. In the New Zealand energy balance these coal energy streams are treated separately.

MBIE data tables classify the coal that is used as a carbon source as "Other Transformation". The current exergy analysis only considers resources that are utilised for their energy content, and not material feedstocks. Therefore, the coal that is used at the NZ Steel mill as a carbon feedstock is not included in this exergy analysis. The NZ Steel mill's waste heat steam generator–turbine set is treated as a transformation process and not an industrial end use, due to the electricity production from the cogeneration system. MBIE data tables classify the rest of the coal used at the NZ Steel mill as "Cogeneration". This is the coal that is utilised to create the process heat product, and from which the waste heat output of the reduction kiln is used as heat input for power generation [1]. In this thesis, we distinguish the difference between these flows by classifying the coal used for energy purposes as an individual transformation process "Cogeneration", and the coal that is used as a carbon feedstock as "Non-Energy Use".

It is important to note here that there are three other users of coal for cogeneration in New Zealand, noted in the "Information on Generating Plants December 2011" table in the 2012 Energy Data File [19]. Kawerau A&B, Kinleith, and PanPac Steam cogeneration are fuelled by biomass, coal and gas. However, the consumption of coal at these plants is negligible compared to total consumption of coal at the NZ Steel mill, so their consumption is not considered separately here.

A small amount of coal (11kg per tonne of steel produced) is also utilised by Pacific Steel, located in Auckland [44]. This site does not utilise waste heat to generate electricity, so the coal utilised by Pacific Steel for the manufacture of steel products is classified as an industrial end-use process. The NZ Steel mill is treated as a transformation process and not an industrial end use due to the electricity generation from waste heat.

Coal is also utilised by various other end users as a heat resource for process heat requirements and in commercial and residential heating end-uses, and are included in the end-use analysis. 17.6PJ of coal is consumed in industrial processes, 0.8PJ in commercial services, 0.2PJ in residential services, and 1.3PJ for agricultural, forestry and fishing processes [26]. A small amount of coal, 0.01PJ (0.03% of total New Zealand consumption), was used for transport as passenger rail end-use. A full list of end-use processes and technologies for coal is included in Appendix B.1.

3.2. Coal Methodology

3.2.1. Coal Physical and Chemical Data

Coal is categorised into three types: bituminous coal, sub-bituminous coal and lignite coal. Each coal type has a different chemical composition, which is used to determine the specific exergy of the coal. Typical composition data for coals around New Zealand were sourced from Rob Boyd at Contact Energy [30]. These compositions, determined using ultimate analysis, are presented in Appendix B.1, as mass fractions of carbon, hydrogen, oxygen, nitrogen and sulphur. The mass data supplied by MBIE is for coal that still contains moisture. This data is converted to dry mass using moisture contents for New Zealand coals in order to calculate exergy values. Coal moisture contents are shown in Table 8.

Table 8. Moisture content of New Zealand coal types [45]

Coal Type	Bituminous	Sub-bituminous	Lignite
Moisture Content (%)	11.2	20.3	41.3

Coal compositions vary within the same coal seam. Mass fractions of carbon at the Huntly coal field range from 76.55% to 67.15%, as seen in Table 66 in Appendix B.1. This variability in coal composition makes it difficult to choose a representative national average composition for coal, so an indicative coal composition was chosen by considering coal fields that produce a higher proportion of the national coal supply. Compositions were also compared to approximate compositions for bituminous coal and lignite coal [31].

Table 9. Coal production volumes and classifications for chosen fields [17]

Location	Coalfield	Gross Coal Production (2013)	Coal Type
Huntly	Huntly Coalfield	192 kt	Sub-bituminous
Rotowaro	Rotowaro Coalfield	1,192 kt	Sub-bituminous
Reddale	Buller Coalfield	1,934 kt	Bituminous
Strongman	Greymouth Coalfield	281 kt	Bituminous
Ohai	Ohai Coalfield	195 kt	Lignite
Newvale	Southland Lignites	287 kt	Lignite

From this analysis, the Rotowaro composition was used for sub-bituminous coal, Reddale composition for bituminous coal, and Newvale composition for lignite coal. Each of these compositions were chosen because they were responsible for the greatest proportion of that coal type production in New Zealand.

With composition data established, ϕ values are determined for each coal type using Equation 11. Specific exergy values are than calculated using Equation 10. Final compositions and specific exergy values are shown in Table 10.

Table 10. Coal compositions and calculated specific exergy values

Coal Type	Bituminous	Sub-bituminous	Lignite
Representative Coal Field	Reddale	Rotowaro	Newvale
Carbon (mass fraction, %)	76.9	75.1	67.8
H (mass fraction, %)	5.3	5.2	4.9
O (mass fraction, %)	15.6	18.2	25.6
N (mass fraction, %)	1.1	1.1	0.9
S (mass fraction, %)	1.1	0.3	0.8
ϕ value	1.06	1.06	1.07
NCV (kJ/kg)	28574	20495	13676
Specific Exergy (kJ/kg)	37731	24081	20078

The mass fractions in Table 10 are DAF (dry ash free).

3.2.2. Electricity generation

Exergy input is calculated from the multiplication of mass flows of coal delivered to electricity generation from MBIE data tables [15] and the calculated specific exergy values for the relevant coal types. Exergy output is the electricity generated, which is sourced from the Electricity Authority [46].

3.2.3. End Use

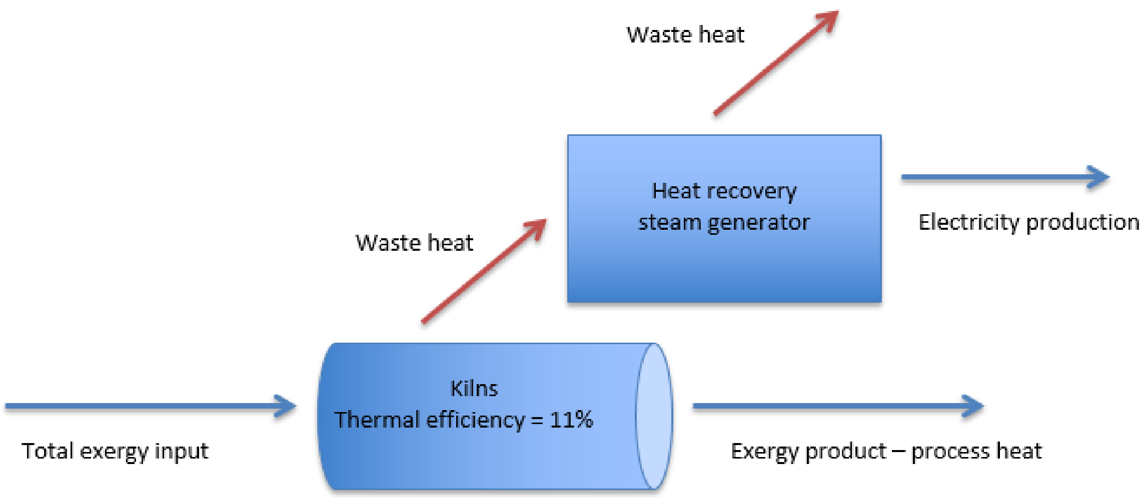
Equation 2 is used to calculate end-use products for heat processes, and non-heat products are calculated using the efficiencies in Table 7. Exergy products and conversion losses were calculated for each end-use process.

3.2.4. Cogeneration

Cogeneration from coal in New Zealand is dominated by the NZ Steel mill. Mass flows of coal delivered to cogeneration processes are multiplied by calculated specific exergy values to find delivered exergy. Again, this input mass flow of coal is defined as

"Cogeneration" coal by MBIE, and is the total coal input that is utilised to create the process heat product. The total exergy output is the sum of electricity produced from cogeneration and the process heat exergy product from the Fe_3O_4 reduction process. The exergy process heat product is calculated using Equation 2. The waste heat from this process is used to generate electricity, which is recorded and supplied by the EA [40]. Electricity is used on-site and delivered off-site to the grid. For the purposes of this analysis, a control volume is created around the cogeneration site, and only the electricity that is delivered to the grid is included as electricity product. Any electricity that is sourced from the grid is calculated as end-use consumption. This means that the total exergy product is the sum of the exergy heat product and the electricity generation that is sold to the grid. The exergy flows are shown in Figure 6 below.

Figure 6. Coal cogeneration exergy flow configuration



1. *Energy Balance*

Total coal energy input to the site is 5.8PJ, supplied by MBIE data tables [15]. Using thermal efficiency for Fe_3O_4 reduction at 11% [47], there is a resulting energy product of 0.6PJ. This energy product is the heat product used for iron reduction. 550GWh of electricity is generated per year from the waste heat from this process, which equals 1.98PJ [34]. Using Equation 22, energy efficiency is 45%.

2. *Exergy Balance*

The coal exergy input to the site is 6.9PJ, calculated from coal specific exergy and delivered mass data from MBIE data tables [15]. The exergetic temperature factor is calculated using Equation 17 and a process temperature of 950°C. Using Equation 17, the exergetic temperature factor is 0.76.

The exergy product from the Fe_3O_4 reduction process is calculated using Equation 16, the exergetic temperature factor calculated above, and the energy product from the Fe_3O_4 reduction process of 0.6PJ. Using Equation 16, the exergy product is 0.5PJ. 550GWh of electricity is generated per year from the waste heat, which equals 1.98PJ [34]. Using Equation 23, exergy efficiency is 36%.

Table 11 below shows the temperature values for calculating energy and exergy flows through the cogeneration system.

Table 11. Temperature values for coal cogeneration calculations

Environmental Temperature (K)	288.2
Exhaust Temperature (K)	1223.2
Exergetic Temperature Factor	0.76

3.3. Coal Results and Analysis

3.3.1. Electricity

The energy and exergy flows for coal electricity generation using the methodology described in section 3.2.2 are shown in Table 12.

Table 12. Electricity generation calculations for coal

	Energy	Exergy
Input (PJ)	10.0	11.7
Output (PJ)	4.6	4.6
Conversion Loss (PJ)	5.4	7.1
Efficiency (%)	46	39

3.2.2. End-Use

Table 13 shows the energy and exergy flows of coal for different end-use sectors.

Table 13. Coal end-use calculations by sector

Sector	Delivered Energy (TJ)	End Use Energy (TJ)	Energy Conversion Loss (TJ)	Energy Efficiency (%)	Delivered Exergy (TJ)	End Use Exergy (TJ)	Exergy Conversion Loss (TJ)	Exergy Efficiency (%)
Agricultural	1276	957	319	75	1510	21	1489	1
Commercial	824	627	197	76	995	32	964	3
Industrial	17648	12994	4654	74	22115	6712	15402	30
Residential	241	81	160	34	309	3	306	1
Transport	12	6	7	47	16	4	12	25
Total	20002	14666	5336	73	24944	6772	18173	27

3.3.3. Cogeneration

The results of cogeneration calculations are presented below in Table 14.

Table 14. Cogeneration calculations for coal

Cogeneration	Energy (PJ)	Exergy (PJ)
Input	5.8	6.9
Thermal Output	0.6	0.5
Product Efficiency	0.1	0.1
Product Output	0.6	0.5
Electricity Output	2.0	2.0
Total Output	2.6	2.5
Conversion Loss	3.2	4.4
Efficiency (%)	45	36

3.3.4. National Energy and Exergy Flows

The energy and exergy flows of the coal resource through New Zealand's energy system are presented in Sankey diagrams, Figure 7 and Figure 8, respectively. Coal stores, such as indigenous production and imports, and coal that is not processed in New Zealand, such as exports, are shown in red. "Other Transformation" consists of coal that is not utilised for its energy and exergy potential, so this is not included in any exergy calculations. End-use sectors are represented by the orange boxes, and transformation processes (electricity generation and cogeneration) are represented as green boxes.

Figure 7. Coal Energy Sankey Diagram, 2014

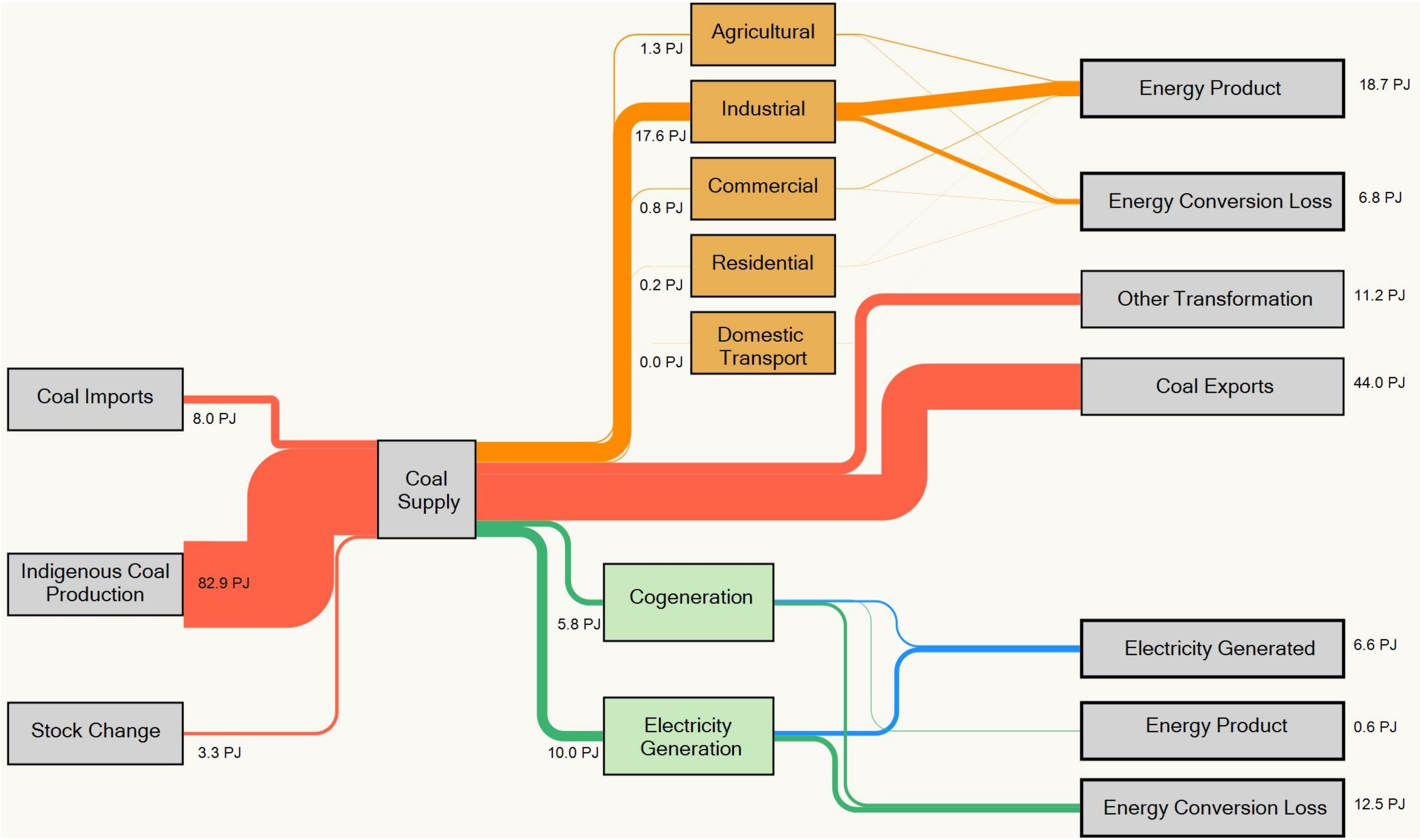
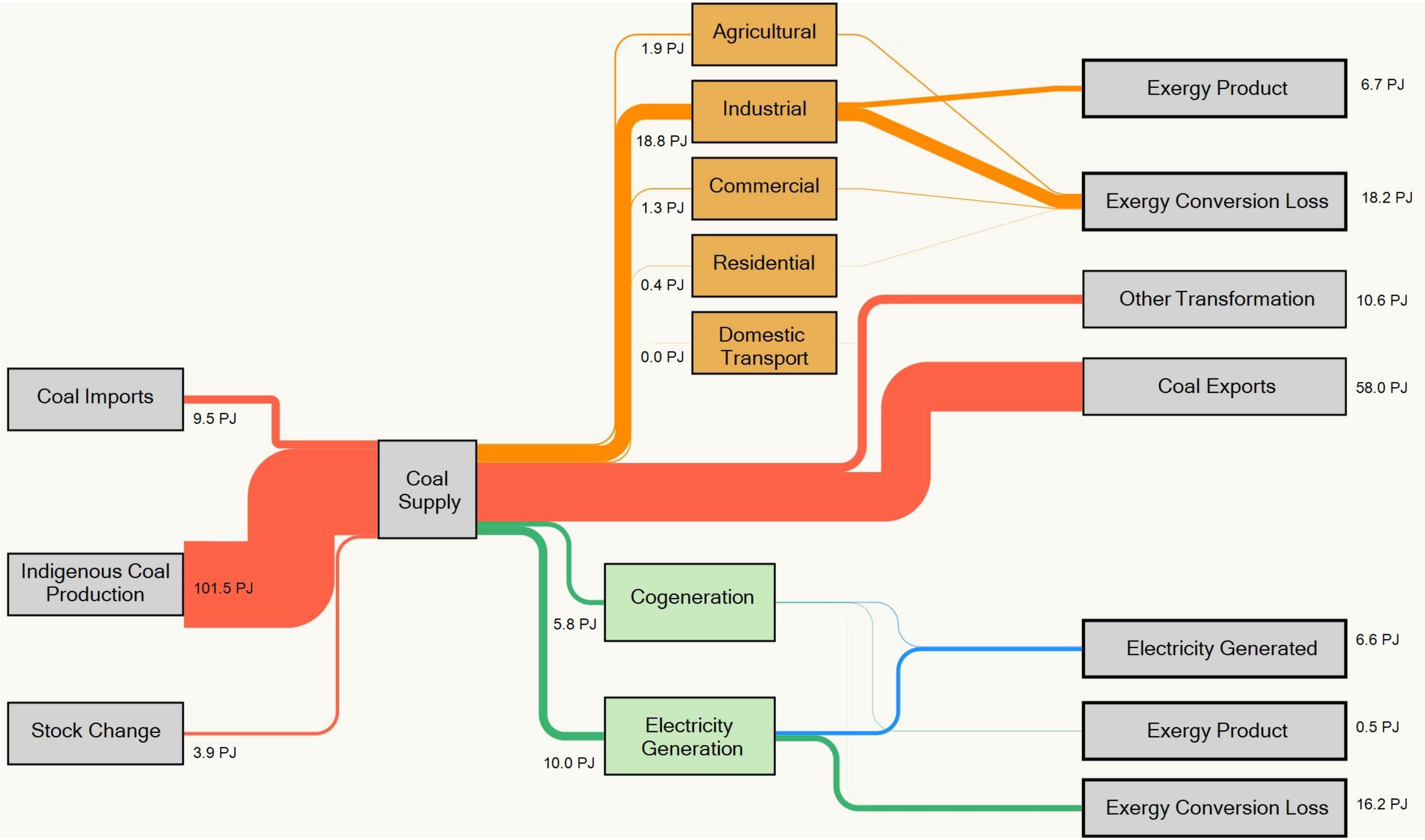


Figure 8. Coal Exergy Sankey Diagram, 2014



3.4. Coal Discussion

Overall, exergy efficiencies are lower than energy efficiencies. This indicates that the coal resource was not being utilised as well as perceived with current energy analysis methods. The following table shows a comparison between energy and exergy efficiencies for transformation and end-use sectors, as well as overall end-use efficiencies. Energy and exergy efficiencies for coal are also included, and this is calculated from total coal inputs into transformation and end-use processes, and total outputs.

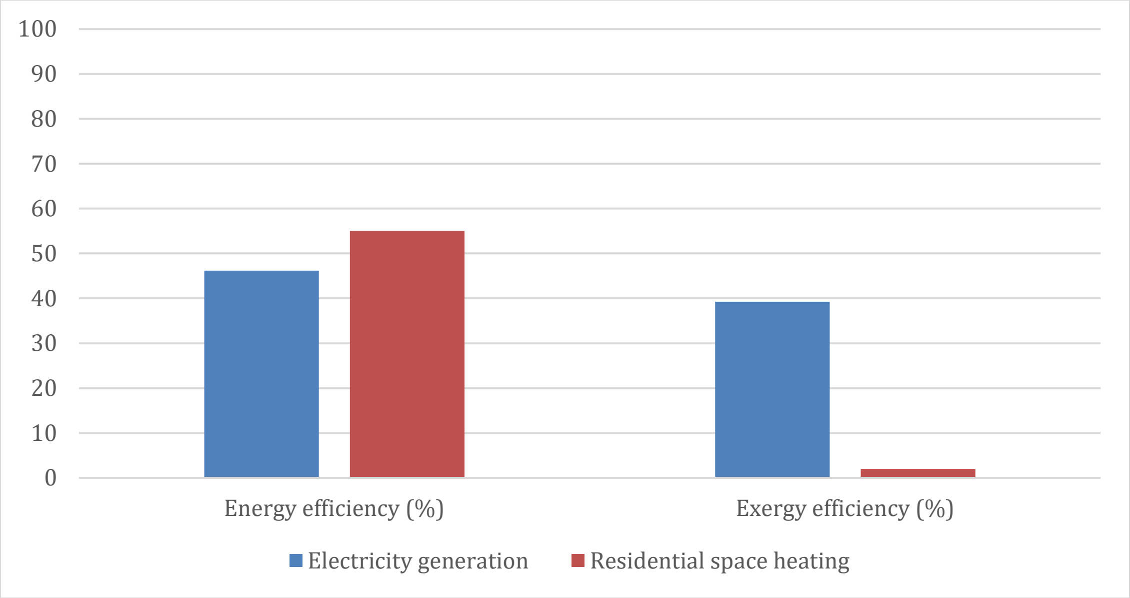
Table 15. Energy and exergy efficiencies for the coal sector

	Energy Efficiency (%)	**Exergy Efficiency (%)**
Electricity Generation (Huntly Power Station)	46	39
Cogeneration (NZ Steel Mill)	45	36
Agricultural Sector	75	1
Industrial Sector	74	30
Commercial Sector	76	3
Residential Sector	34	1
Transport Sector	47	25
Overall Coal	57	29

The major users of coal within New Zealand are electricity generation, cogeneration, and industrial end users, seen in the Sankey diagrams above. These also have the highest exergy efficiencies when compared to other coal exergy processes, as seen in Table 15. This is due to the high-quality outputs, which are electricity and high temperature process heat. From this analysis, it appears that industrial end-use utilises coal exergy better than all other sectors, with the least exergy conversion losses occurring at these sites. The exergy inputs from electricity generation, cogeneration, and industrial end users are utilised more effectively than low exergy sectors, such as Commercial, Residential and Agricultural. The exergy efficiencies are much lower than energy efficiencies in these sectors because they are dominated by low temperature processes, such as boiler and burner systems for space and water heating. The low temperature heat outputs have a low exergy quality. This means that these sectors have proportionally large exergy conversion losses.

An insightful comparison that can be made is between coal that is used for electricity generation at Huntly Power Station, and coal used for residential space heating. Residential space heating appears to be a more efficient use of coal than electricity generation when assessed with an energy analysis. An exergy analysis on the other hand shows that there is much less of the work potential of the resource being utilised in residential space heating. The energy and calculated exergy efficiencies of these processes are shown in Figure 9 below.

Figure 9. Comparison between efficiency values for coal use for electricity generation and space heating in New Zealand.



When the energy and exergy efficiencies of each of these coal uses are compared in Figure 9, it appears that both processes have lower exergy efficiency than energy efficiency. This means that the ability of the technologies to capture the maximum work potential of the input coal is less than that expected from the energy analysis.

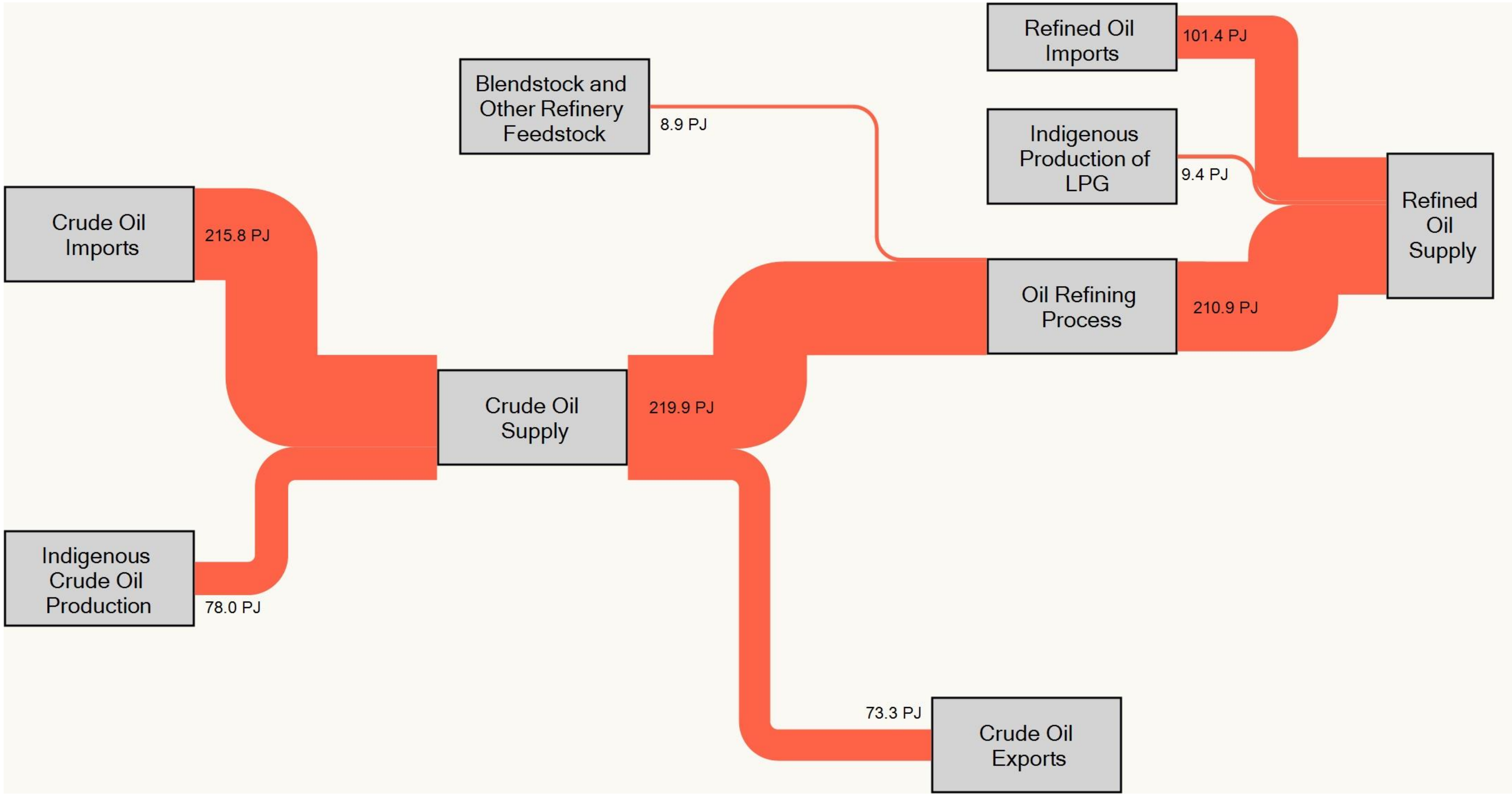
This is again because an exergy analysis accurately assesses the work potential of the resource and products. For electricity generation, the exergy of the inputs is larger than the energy. Electricity generated is the same for energy and exergy analysis, so the overall efficiency decreases. For residential space heating, there is a small increase from energy to exergy of inputs, but the biggest difference is that the exergy of the products is much lower than the energy of the products. This means that the exergy efficiency for residential space heating is much lower than the energy efficiency. The electricity generation process is much better able to capture a high exergy product from the coal inputs than the residential space heating process.

4. Oil

4.1. Oil Use in New Zealand

The largest proportion of primary energy resource use in New Zealand is oil and oil products, making up 31% (238PJ) of TPES in 2014 [15]. Most of New Zealand's oil supply is imported in the form of crude oil [17]. Marsden Point Oil Refinery is the only oil refinery in New Zealand, and in 2014 it processed 5,039,680 tonnes of crude oil, condensate and naphtha. The energy flows of crude oil and refined oil that have been imported or produced in New Zealand are shown in Figure 10.

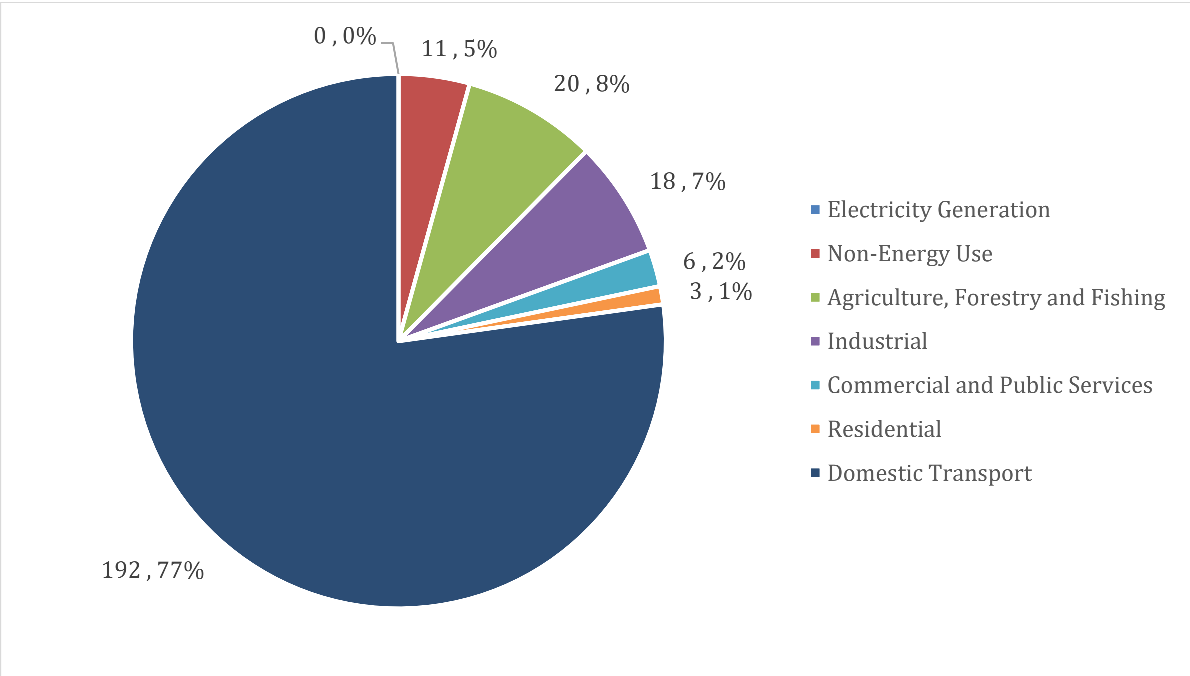
Figure 10. Crude Oil and Refined Oil Energy Flows



LPG production from the natural gas industry is included as liquid fuel products, following practices from MBIE [15]. Some refined oil is used for non-energy use, such as bitumen for roads [15]. A very small amount of oil is used for backup electricity generation.

Approximately 77% (192PJ) of New Zealand's refined oil supply is used for transport purposes [15]. New Zealand's refined oil supply is shown in Figure 11.

Figure 11. Delivered Oil Energy to End Uses and Transformation Processes (PJ), 2015 [15]



Transport is divided into domestic and international transport. Consistent with international practices, international transport is not included in this New Zealand analysis as it is not defined as energy use within the country [17]. Within the agricultural, industrial, commercial and residential sectors, oil is used for motive power, high, intermediate and low temperature process heat from boilers and furnaces, and low temperature space and water heating from burners and boilers.

4.2. Oil Methodology

4.2.1. Oil Physical and Chemical Data

MBIE classify oil and oil products into 12 different types, which can be seen in Table 17. Ultimate analysis composition data for each of these liquid fuel types proved difficult to determine for the range of liquid fuel products [15]. Instead, a typical composition for liquid fuels was sourced from Szargut, Morris and Steward [31]. The ϕ ratio value was calculated for liquid fuels using this typical liquid fuel composition and Equation 14. These methods give a value of ϕ equal to 1.07.

Table 16. Oil composition data and β value [31]

Liquid Fuels	Mass Fraction (%)
Carbon	84.0
Hydrogen	15.0
Sulphur	1.0
ϕ	1.073

Specific exergies were then calculated for each oil fuel type using Equation 10. MBIE provide annual GCV and NCV data for each oil product in their Fuel Properties data table [15].

Table 17. Net calorific value and chemical exergy for each oil product type [15]

Fuel Type	Net Calorific Value (kJ/kg)	Specific Exergy (kJ/kg)
Crude Oil & Condensate	43635	46690
Premium Petrol	43867	46937
Regular Petrol	43913	46987
Petrol	43894	46967
Diesel	42881	45882
Light Fuel Oil	41316	44208
Heavy Fuel Oil	40628	43472
Heavy Bunker Fuel Oil	40349	43174
Jet A1	43288	46318
Avgas	44500	47615
Lighting Kerosene	43600	46652
Bitumen	39120	41858

Each of these specific exergy values are multiplied by the mass flow of the associated fuel type, provided by MBIE Oil Data Table [15], to determine total exergy flow through New Zealand from oil and oil products.

4.2.2. Electricity generation

A small amount of oil is used in New Zealand for electricity generation for back-up purposes. Exergy input is calculated from the mass flows of oil apportioned to Electricity Generation from MBIE data tables [15] and the calculated specific exergy values for the oil types. Exergy output is the electricity generated, which is sourced from the Electricity Authority [46].

4.2.3. End Use

Equation 2 is used to calculate end-use products for heat processes, and non-heat products are calculated using the efficiencies in Table 7. Exergy products and conversion losses were calculated for each end-use process.

4.2.4. Oil Refining

An exergy balance is carried out for oil refining by calculating exergy values of mass flows into and out of the refinery. Mass flows are provided in the MBIE Oil data table [15].

Table 18. Mass balance for oil refining in New Zealand, 2014 [15]

Oil Refining	*Mass (kt)*
Refinery Intake	5,242.8
Crude Oil, Condensate and Naphtha	5,039.7
Blendstocks and other refinery feedstocks	203.1
Refinery Fuel and Losses (calculated)	333.7
Refinery Output	4,909.1
Petrol	1,300.2
Regular Petrol	1,009.3
Premium Petrol	290.9
Diesel	1,863.4
Fuel Oil	634.8
Aviation Fuels	960.8
Jet A1	960.8
Other Petroleum Products	149.9

4.3. Oil Results and Analysis

4.3.1. Electricity Generation

Energy and exergy flows for electricity generation from oil are given in Table 19.

Table 19. Electricity generation calculations for oil

	Energy	Exergy
Input (PJ)	0.02	0.02
Output (PJ)	0.01	0.01
Conversion Loss (PJ)	0.01	0.02
Efficiency (%)	40	38

4.3.2. End-Use

Calculated energy and exergy flows for different end-use sectors are given in Table 20.

Table 20. Oil end-use calculations by sector

Sector	Delivered Energy (TJ) [26]	End Use Energy (TJ) [26]	Energy Efficiency (%)	Energy Conversion Loss (TJ) [26]	Exergy Efficiency (%)	Delivered Exergy (TJ)	End Use Exergy (TJ)	Exergy Conversion Loss (TJ)
Agricultural	20163	4539	23	15624	19	21575	4163	17411
Commercial	5530	1871	34	3659	15	5917	881	5035
Industrial	17535	8286	47	9249	22	18763	4115	14648
Residential	2734	1992	73	742	1	2926	39	2887
Transport	191806	33722	18	158083	17	205232	34030	171202
Total	237768	50425	21	187344	17	254412	43229	211183

4.3.3. Oil Refining

Calculated energy and exergy flows for oil refining are given in Table 21.

Table 21. Energy and exergy balance for oil refining in New Zealand

Oil Refining	*Energy (PJ)*	*Exergy (PJ)*
Refinery Intake	228.8	244.8
Crude Oil, Condensate and Naphtha	219.9	235.3
Blendstocks and other refinery feedstocks	8.9	9.5
Refinery Fuel and Losses (calculated)	17.8	19.1
Refinery Output	210.9	225.7
Petrol	57.1	61.1
Regular Petrol	44.3	47.4
Premium Petrol	12.8	13.7
Diesel	79.9	85.5
Fuel Oil	25.8	27.6
Aviation Fuels	41.6	44.5
Jet A1	41.6	44.5
Other Petroleum Products	6.6	7.0

4.3.4. National Energy and Exergy Flows

Flows of refined oil through New Zealand are shown below in Figure 12 and Figure 13, the refined oil energy and exergy Sankey diagrams. These figures are restricted to refined oil flows for clarity within the diagrams. Energy flows of crude and refined oil that make up the refined oil supply are shown in Figure 10. Note that oil for non-energy use and electricity generation were so small in proportion to other oil uses that they were not included in the overall Sankey diagrams. Stock in transit and refined oil exports were also excluded, as the flows were too small.

Figure 12. Refined Oil Energy Sankey Diagram, 2014

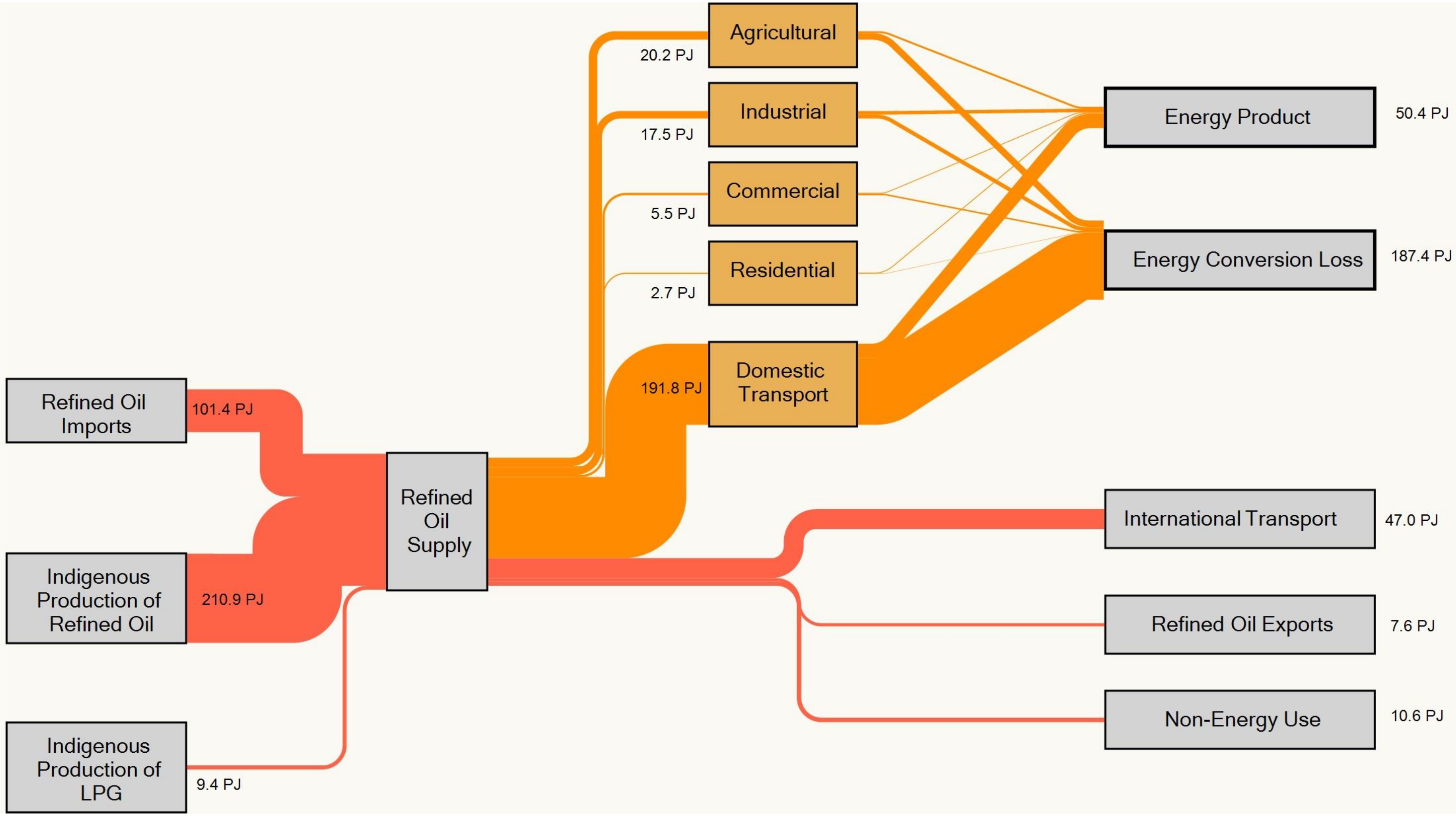
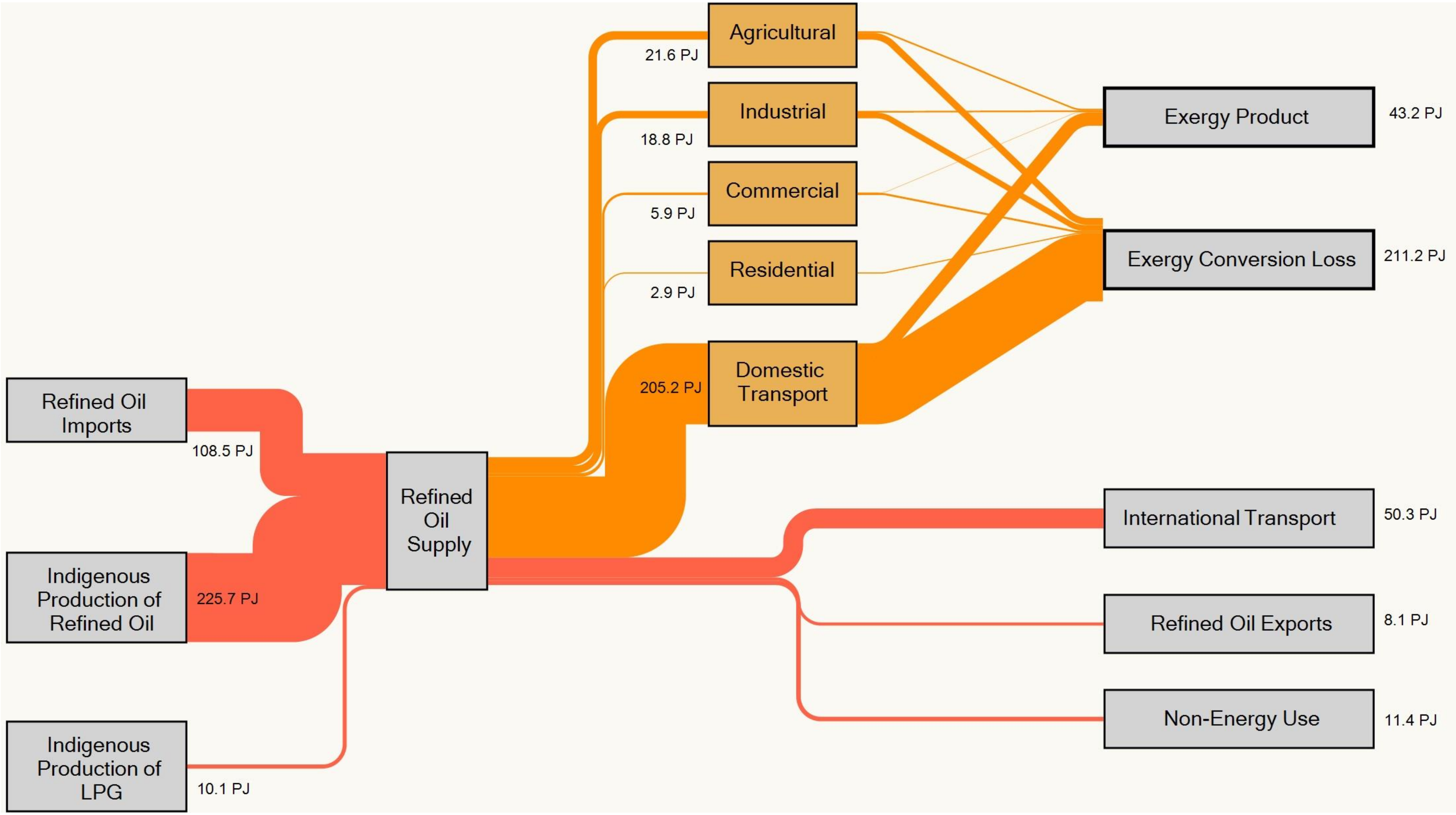


Figure 13. Refined Oil Exergy Sankey Diagram, 2014



4.4. Oil Discussion

The overall energy and exergy efficiencies for each transformation process and end-use sector are shown in Table 22.

Table 22. Energy and exergy efficiencies for the oil sector

	Energy Efficiency (%)	Exergy Efficiency (%)
Electricity Generation	40	38
Oil Refining	92	92
Agricultural Sector	23	19
Industrial Sector	47	22
Commercial Sector	34	15
Residential Sector	73	1
Transport Sector	18	17
Overall Oil	21	17

Like the coal efficiency results, exergy efficiencies are lower than energy efficiencies. The only exception to this is electricity generation, where the efficiencies are identical as the amount of fuel being processed is so small that any difference between the energy and exergy input values is negligible. Both the energy and exergy efficiency calculations use the same electricity production as the exergy output, so this means the resulting efficiencies are very similar. In oil refining, crude oil is processed into refined oil. There are few energy and exergy losses from the oil that is being processed, as the fuel is changing chemical structure to be utilised for different processes, rather than being consumed for a heat or work output. Other fuels, such as end-use consumption of oil products and electricity, drive this process, and their losses are included in the end-use process calculations.

Typically, oil end-use sectors that are dominated by motive power and transport do not see as much of a drop in efficiency as those dominated by low temperature heat processes, due to the higher quality in the final exergy product. Per Equation 2, low temperature heat is a low exergy product, while work and high temperature heat are high exergy products. The agricultural sector is dominated by motive power and high temperature heat processes, and thus exergy efficiency is only slightly lower than energy efficiency. The industrial and commercial sectors utilise oil for a range of processes, with both high and low exergy outputs. There is a larger drop in efficiency for these sectors due to the low temperature heat processes, such as boiler systems for space heating.

There is a major drop between the efficiencies in the residential sector. The processes here are burners for direct heat. The work potential of the input fuel is not utilised fully and there are major exergy conversion losses occurring within the residential sector, which indicates that oil should not be utilised for these processes, but should be replaced with other fuels and processes for the same product with less exergy conversion loss. The oil that would otherwise be used for these processes could be used for processes with higher exergy efficiencies, which would reduce national exergy conversions losses.

From an energy analysis, it would appear that using oil for low temperature heat processes is one of the more efficient ways to use oil, as the energy efficiency for the residential sector is 73%. The exergy analysis shows that the maximum work potential of the oil is far from being reached, and that these processes are some of the least efficient, with an exergy efficiency of 2%.

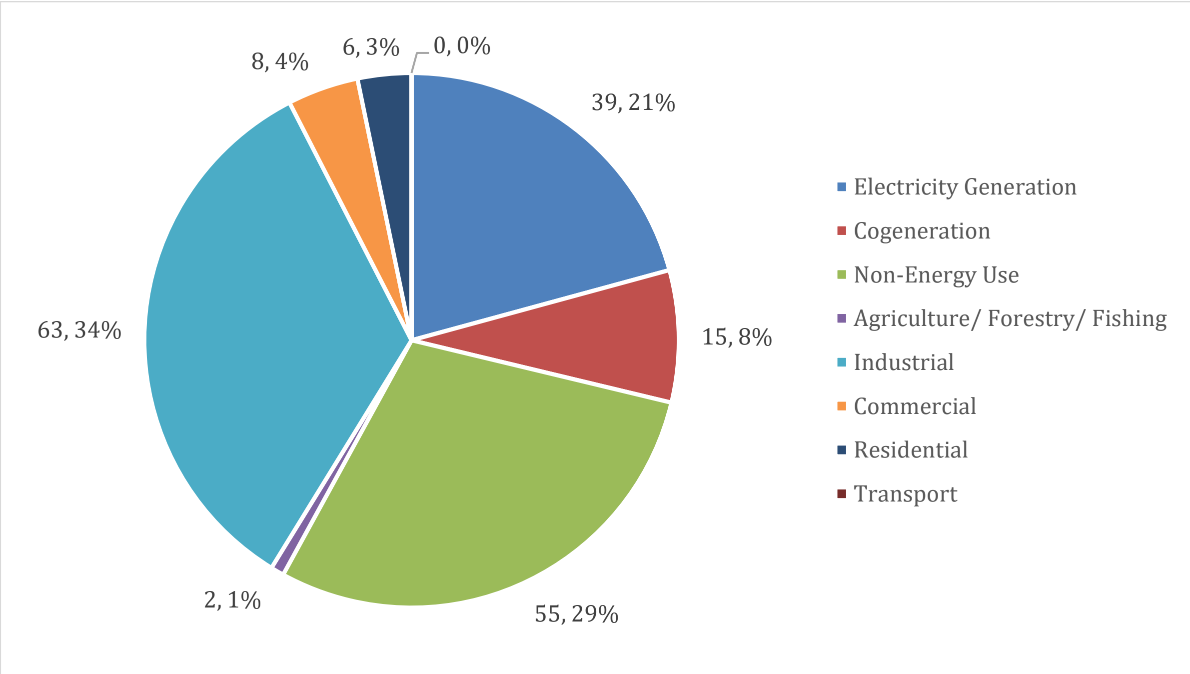
The transport sector, which dominates oil consumption in New Zealand, has low energy and exergy efficiencies, indicating large losses in this sector. The transport sector is responsible for the largest use of oil in New Zealand, so the energy and exergy conversion losses occurring here have a large impact on the overall losses in New Zealand. These results indicate that alternative energy resources should be utilised for transport purposes, such as electricity in electric vehicles. An additional study into the impacts of converting to an electric vehicle fleet with both energy and exergy analyses would be an interesting way to examine methods for reducing exergy conversion losses within New Zealand.

5. Natural Gas

5.1. Natural Gas Use in New Zealand

Natural gas makes up 18% (133PJ) of New Zealand's TPES, shown in Figure 1, the majority of this being used for electricity generation, non-energy use, and industrial end-use process.

Figure 14. Delivered Natural Gas Energy to End Uses and Transformation Processes (PJ), 2015 [15]



The breakdown in natural gas use in New Zealand can be seen in Figure 14. 29% (54PJ) of New Zealand's natural gas supply is used for electricity generation and cogeneration. 16% (24PJ) of New Zealand's total electricity is produced from natural gas [15]. All the gas fields in New Zealand are located in the Taranaki region of the North Island, so natural gas consumption is limited to the North Island of New Zealand. There are no imports or exports, due to the difficulties involved with storing and transporting natural gas.

Genesis Energy Limited (Huntly – including the unit 5 combined cycle plant) and Contact Energy Limited (Otahuhu B, Taranaki Combined Cycle and Stratford) are the main electricity generators in New Zealand using natural gas [40]. In cogeneration processes, electricity is generated from natural gas driven steam turbines, and the waste heat is utilised as process heat. Natural gas cogeneration is dominated by milk drying processes, such as those at Kapuni, Hawera, and Te Rapa. A full list of natural gas electricity generating power stations and cogeneration systems can be found in Appendix D.1. Interestingly, the NZ Steel mill is listed as having gas cogeneration processes in this table because the by-product gasses from the direct reduction iron-making process are used for electricity generation. In this thesis, the NZ Steel mill cogeneration is classified as coal cogeneration, as the gas by-products are from coal consumption, and natural gas is not consumed in the process.

Another major use for natural gas is industrial end-use processes. This sector is dominated by the boiler systems that supply heat to methanol and ammonia/urea production processes. Methanol and ammonia/urea production also consumes gas defined as non-energy gas [15]. The gas allocated to non-energy use is not included in this exergy analysis, as it is a chemical feedstock and not use for energy processes [15]. Non-energy gas accounted for 29% (55PJ) of New Zealand's natural gas consumption in 2014. When gas consumption in industrial end-use processes and non-energy gas are considered as a whole, total methanol and ammonia/urea production consumed 46% (66PJ) of New Zealand's total natural gas supply in 2014.

The remaining natural gas is used in the agricultural, commercial, residential, and transport sectors, as well as other industrial end-use processes. The gas is used for cooking, space and water heating, transport and process requirements.

5.2. Natural Gas Methodology

5.2.1. Gas Physical and Chemical Data

Natural gas is produced at a number of fields in New Zealand, leading to a variety of natural gas compositions. A generalised natural gas composition was used in this analysis due to a lack of available field data and recognition that blending does occur before gas transmission. This composition can be seen as molar fractions in Table 23.

Table 23. Natural Gas General Molar Fraction Data [31]

General Natural Gas Composition	Mole Fraction (%)
Methane	92
Ethane	2
Nitrogen	6

A sample chemical composition for the Kapuni gas field in also included in Appendix D.2, but this composition is for the gas before it has been through processing to remove CO_2, H_2S and heavier hydrocarbons prior to transmission, so it is not a representative composition of natural gas flows around New Zealand [48]. In order to calculate the specific exergy, mole fraction data was converted to mass fractions, shown in Table 24 below.

Table 24. Natural Gas General Mass Fraction Data [31]

General Natural Gas Composition	Mass Fraction (%)
Carbon	68
Hydrogen	22
Oxygen	0
Nitrogen	10
Sulphur	0

A ϕ value of 1.04 is calculated using Equation 15 for gaseous fuels. Specific exergy is calculated using Equation 10. A weighted average NCV of 28034 kJ/kg is supplied by MBIE for New Zealand natural gas [15]. This results in a specific exergy of 29155 kJ/kg for natural gas.

As MBIE provide volumes of gas flow through New Zealand, this specific exergy was converted to its volumetric equivalent using a density of 1.30 kg/m^3 [15] resulting in a specific exergy of 37901 kJ/m^3. The volumetric specific exergy value is directly multiplied by MBIE volume flow data to find exergy flows.

5.2.2. Electricity Generation

Exergy input is calculated from the multiplication of natural gas specific exergy and the volume of natural gas delivered to Electricity Generation from MBIE data tables [15]. Exergy output is the electricity generated, which is sourced from the MBIE Electricity Data Table [15].

A full list of electricity generating stations can be found in Appendix D.1.

5.2.3. End Use

Volume flows of gas to different end use processes and sectors are multiplied by the converted specific exergy to find delivered exergy. Equation 2 is used to calculate end-use products for heat processes, and non-heat products are calculated using the efficiencies in Table 7.

5.2.4. Cogeneration

The turbine for the Te Rapa facility is used as a representative for all natural gas cogeneration plants in New Zealand and is a G.E Frame 6B.03 gas turbine [40]. This power station provides steam and electricity to Fonterra's Te Rapa factory, which is one of the world's largest milk powder drying plants [40]. Heat energy production from the exhaust output is calculated from exhaust energy per hour. Generating hours are approximated from the total 2014 electricity generation in PJ from all cogeneration sites and the rated generation for the gas turbine in MW. For exergy analysis of the cogeneration system, the thermal exergy product is calculated using an exergetic temperature factor and Equation 16. The environmental temperature is the average New Zealand temperature, and the process temperature is 548°C, which is exhaust temperature of the 6B.03 gas turbine [49]. The exergetic temperature factor is multiplied by the thermal efficiency to get thermal exergy efficiency, and finally this exergy efficiency is used to calculate the thermal exergy output. Energy and electricity data are sourced from the "Electricity" and "Renewables" MBIE data tables [15]. Total plant output is the sum of thermal product and electricity generation. Overall plant efficiency is calculated from total plant output and total plant input.

Table 25. Cogeneration assumptions for natural gas

Cogeneration	Energy
Environmental Temperature (K)	288.2
Exhaust Temperature (K)	821.2
Exergetic Temperature Factor	0.6
Net Output (MW)	44.0
Time generating (hr)	29106.7
Exhaust Energy (MM kJ/hr)	305.0

*This is the total generating hours for all natural gas cogenerating plants in New Zealand.

This method presumes that all steam product from the cogeneration system is utilised by the end-use process. This analysis assesses the ability for the current system to produce electricity and a steam product that can be utilised by end-use processes.

A full list of cogeneration sites can be found in Appendix D.1.

5.3. Natural Gas Results and Analysis

5.3.1. Electricity Generation

Energy and exergy flows for electricity generation from natural gas are given in Table 26.

Table 26. Electricity generation calculations for natural gas

Electricity Generation	Energy (PJ)	Exergy (PJ)
Input	39.1	40.7
Output	19.0	19.0
Conversion Loss	20.1	21.6
Efficiency (%)	49	47

5.3.2. End-Use

Exergy products and conversion losses were calculated for each end-use process, and these results are shown below in Table 27.

Table 27. Natural Gas end-use calculations by sector

Sector	Delivered Energy (TJ)	End Use Energy (TJ)	Energy Efficiency (%)	Energy Conversion Loss (TJ)	Exergy Efficiency (%)	Delivered Exergy (TJ)	End Use Exergy (TJ)	Exergy Conversion Loss (TJ)
Agricultural	1517	1290	85	228	2	1578	24	1554
Commercial	8101	6421	79	1676	4	8425	319	8106
Industrial	63375	51038	81	11963	38	65910	25274	40637
Residential	6097	4210	69	1887	6	6341	401	5940
Transport	20	3	13	18	12	21	2	18
Total	79111	62962	80	16150	32	82276	26021	56255

5.3.3. Cogeneration

Energy and exergy flows for cogeneration are shown in Table 28.

Table 28. Cogeneration calculations for natural gas

Cogeneration	Energy	Exergy
Input (PJ)	15.0	15.6
Electricity Output (PJ)	4.6	4.6
Thermal Output (PJ)	8.9	6.0
Total Output (PJ)	13.5	10.6
Conversion Loss (PJ)	1.5	5.0
Thermal Efficiency (%)	59	38
Electricity Generating Efficiency (%)	33.5	29.5
Overall Plant Efficiency (%)	90	68

5.3.4. National Energy and Exergy Flows

Overall gas energy and exergy results are provided in Figure 15 and Figure 16. These figures give an idea of the magnitude of exergy flow to each transformation and end-use process, as well as the proportions of exergy products and exergy conversion losses from each process. As small amount of natural gas is utilised for domestic transport, and set aside for stock change, but these are so small that they cannot be seen clearly in the figures.

Figure 15. Natural Gas Energy Sankey Diagram, 2014

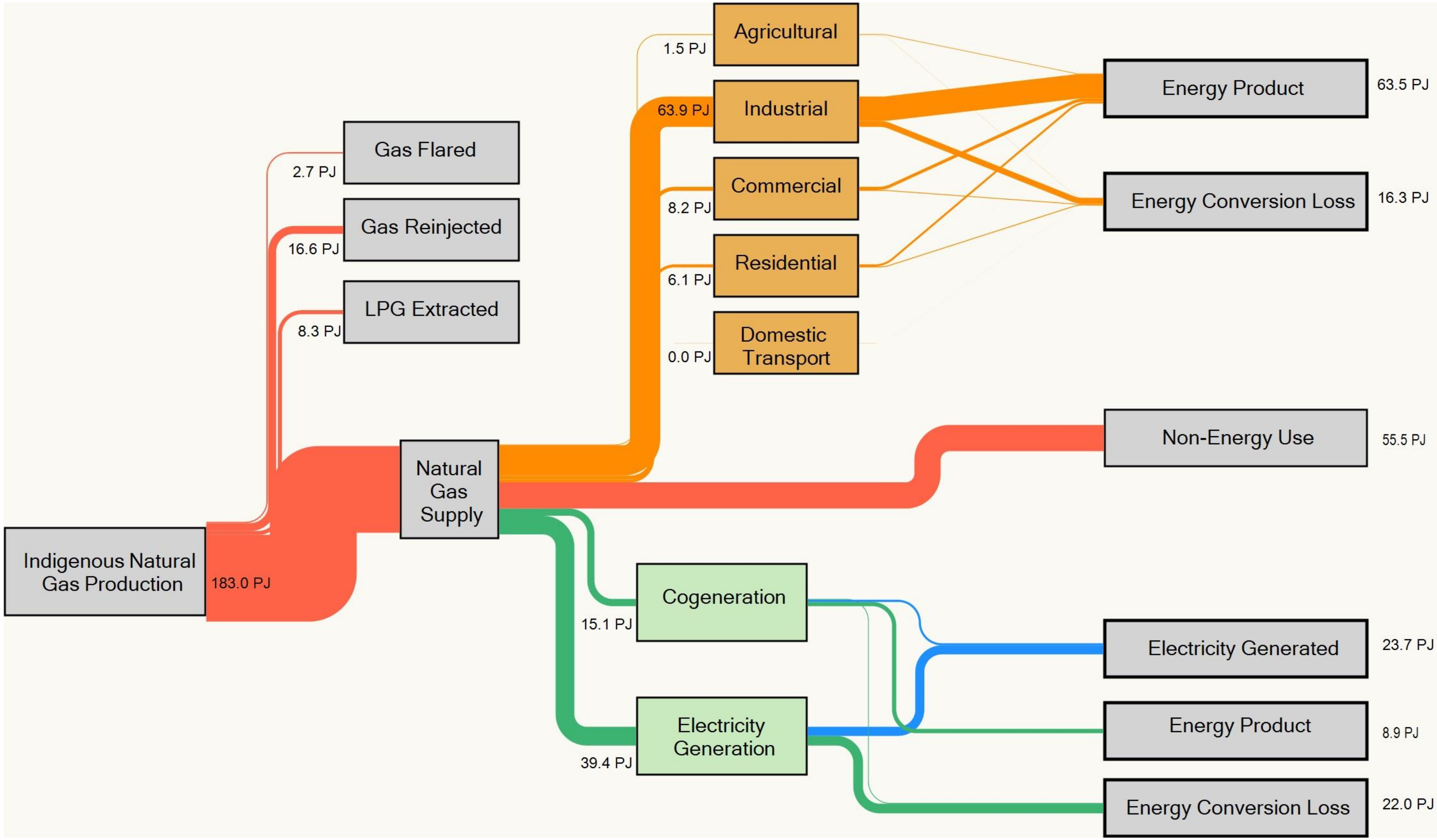
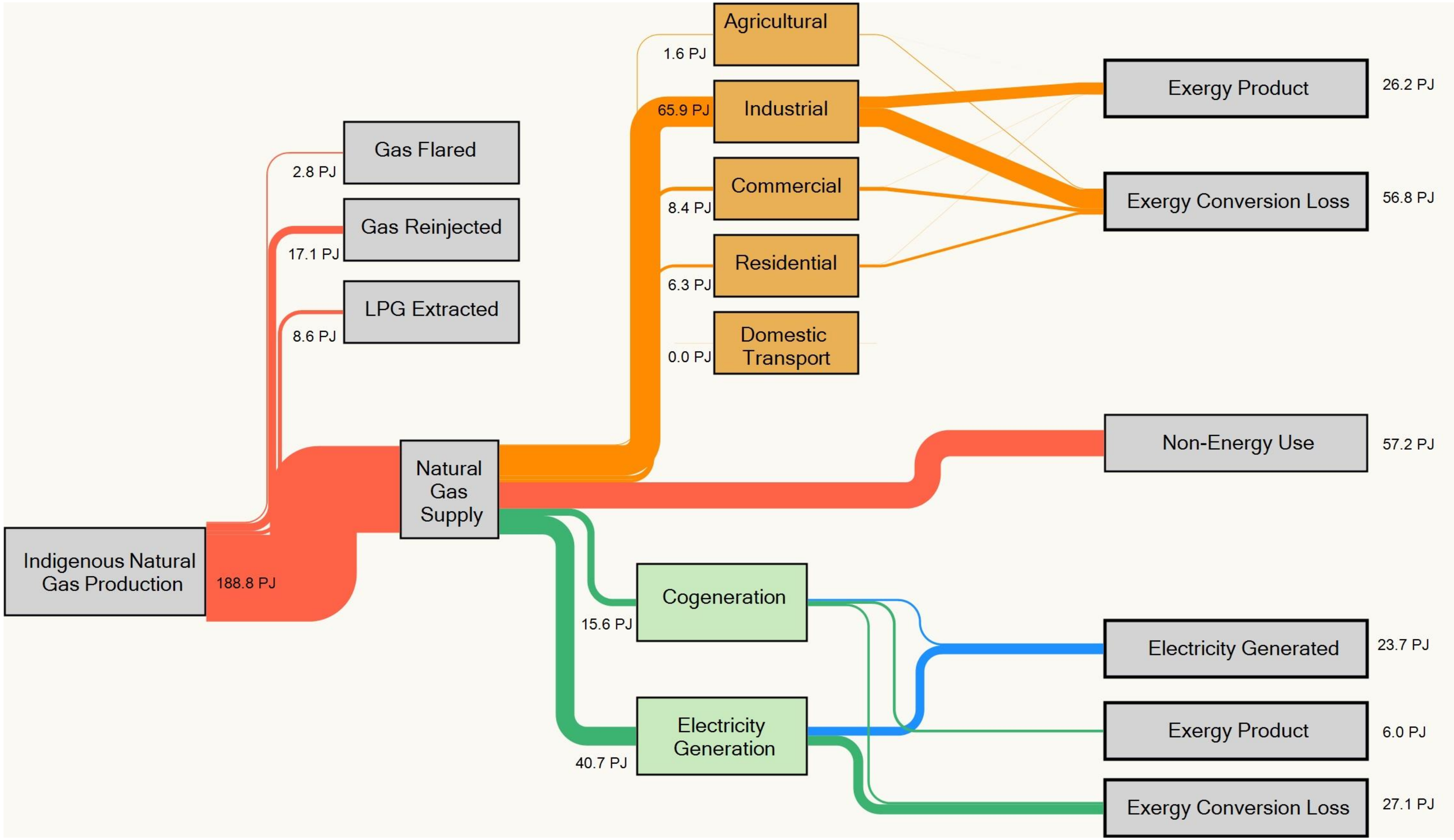


Figure 16. Natural Gas Exergy Sankey Diagram, 2014



Natural gas consumption is dominated by electricity generation and methanol and ammonia/urea production. Methanol and ammonia/urea production consumes the "non-energy use" natural gas, as well as a large proportion of industrial end-use natural gas.

5.4. Natural Gas Discussion

Energy and exergy efficiencies for each transformation process and end-use sector are shown below in Table 29.

Table 29. Energy and exergy efficiencies for the natural gas sector

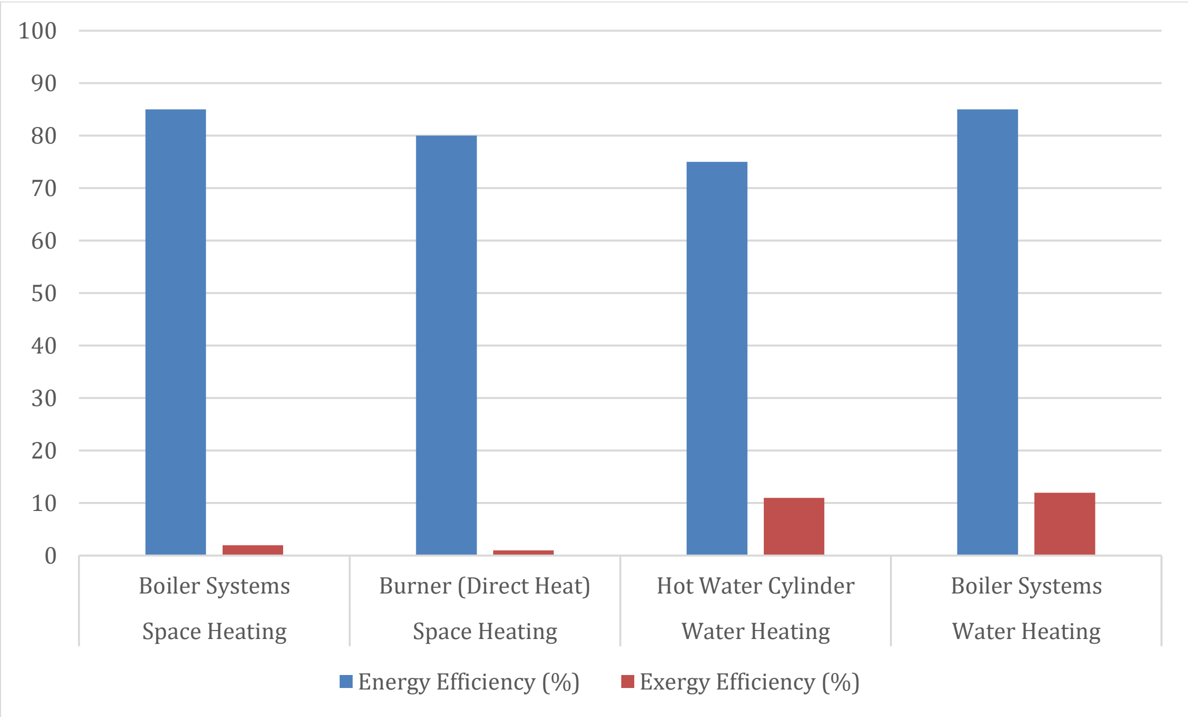
	Energy Efficiency (%)	Exergy Efficiency (%)
Electricity Generation	48	46
Cogeneration	89	68
Agricultural Sector	85	2
Industrial Sector	81	38
Commercial Sector	79	4
Residential Sector	69	6
Transport Sector	13	12
Overall Natural Gas	72	41

There is very little difference in energy and exergy efficiency for electricity generation. The energy and exergy product from these processes is the electricity that is generated, and the exergy of electricity is equal to its energy [28]. Energy and exergy inputs are very similar for natural gas because the ϕ value is close to unity, so specific exergy and specific energy are very close. When the energy and exergy inputs and outputs are close, the resulting efficiencies are similar as well.

The analysis of cogeneration systems is similar to that of the electricity generation systems, in that specific energy and exergy are similar, and there is the same electricity generation in both energy and exergy analysis. The key difference is that the waste steam is now utilised as a heat product. Cogeneration appears to have a very high efficiency because this analysis assumes that the entire steam product is utilised. The steam product is very different when assessed with exergy analysis compared to energy analysis. The quality of the steam is considered in an exergy analysis, so the exergy of the heat product is lower than the energy. The lower exergy of this steam compared to the energy of the steam, which is the reason for a lower exergy efficiency than energy efficiency. The steam is a high temperature product at 548°C, which means the steam product has a relatively high work potential when compared to a low temperature steam product. The exergy efficiency is still very high for cogeneration processes at 67%, due to the relatively high quality of the steam product, and also due to the assumption that all of this steam product is utilised. In reality, some of this steam would not be utilised as a heat product.

The temperature of the exergy product also has implications in the heat generating processes in the end-use sectors. The high temperature processes generate a higher quality product from the input natural gas that the low temperature processes. For this reason, the industrial sector which is dominated by high temperature boiler and furnace processes has a higher exergy product than the agricultural, commercial and residential sectors, which are dominated by low temperature processes such as space and water heating. This is reflected in the efficiencies of these sectors, where the apparently high energy efficiencies (85% for agricultural. 80% for commercial, and 69% for residential) are much lower when assessed with exergy analysis (2% for agricultural. 4% for commercial, and 7% for residential). Space heating is carried out using boilers systems and burners for direct heat, and water heating is carried out using hot water cylinders and boiler systems. A table of energy and exergy efficiencies for these technologies is shown below.

Figure 17. End-Use Technology Energy and Exergy Efficiencies for Space and Water Heating



Using the results of an energy analysis on these sectors, space heating processes and water heating processes appear to be similarly efficient. The results from the exergy analysis indicate that the space heating processes are less efficient that the water heating processes. This is again due to the process temperatures. Space heating has been analysed at 17.3°C, and water heating at 60°C, so water heating produces a higher quality heat product.

6. Geothermal

6.1. Geothermal Use in New Zealand

The premise for this thesis is that energy analyses do not consider the quality of energy resources or their transformations, and that a second law exergy analysis provides more information about the potential utility of an energy resource. This is especially true for geothermal energy systems. From the MBIE "Energy in New Zealand" report, "As geothermal fluid is much lower in temperature than steam produced by a coal or gas boiler, the transformation efficiency of geothermal energy is significantly lower" [50]. Typically, geothermal fluid is a low-quality energy resource compared to that from coal, oil or natural gas resources. Energy analyses do not account for the thermodynamic quality of the energy resource. This means that the energy efficiency of a geothermal power plant appears to be very low, because the electricity produced from the power plant is very small relative to the apparently large energy input. Exergy analysis offers a better understanding of the quality of the input resource, and provides a better basis for assessing efficiency.

Geothermal resources provide a large proportion of New Zealand's electricity, 16% in 2014 as seen in Figure 3, and are likely to contribute more in a low carbon future. Understanding the geothermal resource use has a major impact on the overall understanding of New Zealand's total resource efficiency and use.

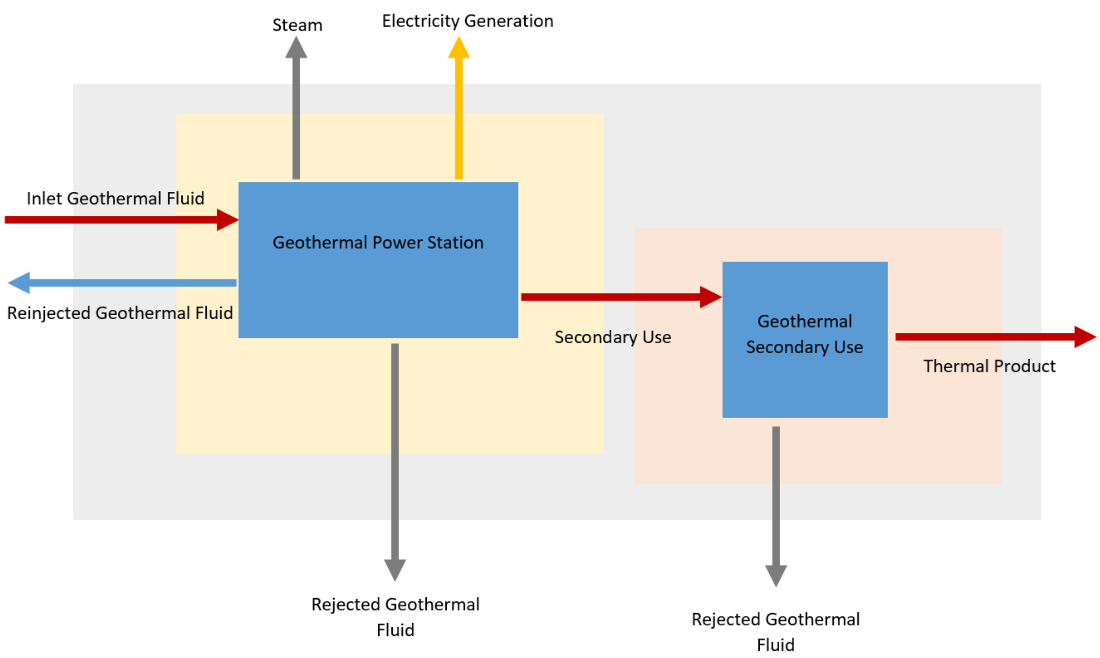
In New Zealand, geothermal energy is classified into electricity generation, secondary use, and direct use applications. Secondary use is sometimes classified as cogeneration, as the separated fluid from electricity generating sites is utilised by the secondary use sites as a thermal input for low temperature heating products. The definition of cogeneration from the Ministry of Economic Development is:

"The simultaneous or sequential production of two or more forms of useful energy from a single primary energy source. ... a cogenerator is an electricity-generating facility that produces electricity and a form of useful thermal energy (such as heat or steam for industrial or commercial heating or cooling purposes)" [19]

In geothermal "cogeneration", the electricity generation and useful thermal energy use occurs at two different sites, so the term "Secondary Use" has been chosen to describe this cascaded system of geothermal resource use in this report.

Figure 18 below is a generalised depiction of the interactions between geothermal power stations and geothermal secondary use.

Figure 18. Exergy Flows for Geothermal Power Stations and Secondary Use



97% (195PJ) of the geothermal energy resource is delivered to electricity generation sites. This occurs mostly in the Taupo Geothermal Region in the North Island. Geothermal fluid is extracted from the reservoir, dry steam is separated and processed through a binary or tertiary power plant to generate electricity, and waste is rejected and/or re-injected into the reservoir. Separated 'wet' geothermal steam from these power plants is often utilised by industrial processes, such as the Wairakei Prawn Farm. These are defined in this report as Secondary Uses. Table 30 below includes the names of all major electricity generating power stations and secondary use sites in New Zealand, and the name of the geothermal field they source their steam from. Sources of data for each power station and secondary use are referenced within this table.

Table 30. Locations of Geothermal Power Stations and Secondary Use in New Zealand

Geothermal Field	Power Station	Secondary Use
Kawerau	Kawerau Power Plant [51], [52], [32]	
	KA24 [53], [32], [40], [52]	
	Kawerau Binary, TG01 and TG02 [54], [52], [32]	
		Norske Skog Tasman Pulp and Paper Mill [27]
		Carter Holt Harvey Tasman Wood production [27]
		SCA Hygiene Australia [27]
Mokai	Mokai Power Plant -1, 2, 1A. [48], [55], [40], [52], [32]	
		Mokai Glass House [56], [32], [57], [58]

		Miraka Whole Milk Powder Plant [57], [32], [35], [26], [27]
Ngatamariki	Ngatamariki Power Station [59], [60], [40], [52], [32]	
Nhawha	Ngawha Power Station [48], [61], [40], [32]	
Ohaaki – Broadlands	Ohaaki Power Station [48], [52], [40], [32], [62]	
		Ohaaki Thermal Kilns [27], [32], [57]
Rotokawa	Rotokawa Power Station [63], [40], [52], [32]	
	Nga Awa Purua Power Station [51], [53], [40], [52]	
Tauhara	Te Huka Power Station [64], [32]	
		Tenon Kilns [27], [32], [57], [64]
Wairakei	Wairakei Binary Power Station [24], [64]	
	Poihipi Road Power Station [24], [64]	
	Te Mihi Power Station [64], [55]	
		Wairakei Prawn Farm [27], [32], [57]
		NETCOR Tourism Facility [27], [32], [57]
		Wairakei Resort Hotel [27], [32], [57]

Geothermal steam is also used directly on a small scale throughout New Zealand, and this consumption is defined as Direct Use. Direct use makes up 3% of geothermal energy consumption in New Zealand. Most of this use is bathing and swimming, and the remainder is space and water heating, some greenhouse heating, and other uses. The data for direct geothermal use is supplied in the 2014 Assessment of Geothermal Direct Use Data [27].

6.2. Geothermal Methodology

6.2.1. Electricity generation

Geothermal consumption is dominated by electricity generation. The exergy of geothermal fluid inputs is calculated from temperature and pressure data. These data are used to calculate enthalpy and entropy values, which are input into Equation 5 to calculate specific exergy.

Inlet geothermal fluid is sourced from geothermal bore field wells. Some of this fluid is re-injected into the reservoir after being used to generated electricity. From the data that was available, it was estimated that 35% of fluid is re-injected. This is based on the ratio of fluid withdrawn from the reservoir to re-injected fluid at the Wairakei Geothermal Power Station [24]. Exergy of electricity outputs are taken to be the same as their energy values. Electricity generation data is sourced from the 2012 Generating Stations List from the Electricity Authority [40]. Some net generation values are sourced from the Wairakei and Tauhara Geothermal System Annual Monitoring Report [64]. Losses from electricity generation include waste/ rejected fluid, the exergy losses within the system, and exergy destruction that occurs on site. Based on these assumptions, an exergy analysis is carried out for each geothermal power station.

Exergy efficiencies of each geothermal power station are assessed using the exergy of inlet and outlet fluid flows, as well as the electricity that is produced. Figure 18 shows the exergy inlets and outlets for a general geothermal power plant. The following equation is used to calculated efficiency of the electricity generating site, and corresponds to flows passing through the yellow area in this figure.

Equation 24:

$$\varphi_{elec\ gen} = \frac{W_e}{B_{in} - B_{re-injected}}$$

In the efficiency calculations, the net (input minus re-injected) exergy of the input geothermal fluid is used

6.2.2. Secondary Use and Direct Use

The exergy of the utilised geothermal fluid is calculated in the same way as for geothermal electricity generation. The enthalpy and entropy of the inlet and product geothermal fluid is calculated from temperature and pressure data, and specific exergy is calculated from Equation 5. This is multiplied by the mass flow rate to find total exergy inputs and products. We calculate the combined waste exergy from conversion, destruction and rejection as the difference between the usable input and product. These flows for secondary use can be seen passing through the orange box in Figure 18. The efficiency for secondary use and direct use is calculated from the thermal product and the delivered geothermal fluid.

Equation 25:

$$\varphi_{secondary\ and\ direct\ use} = \frac{B^Q}{B_{in}}$$

This analysis is carried out for each geothermal secondary use and direct use processes.

6.2.3. Kawerau Secondary Use

In this thesis, the Kawerau secondary use system was analysed as a separate system from other secondary uses, as there were multiple interactions between each secondary use site. This secondary use system includes geothermal fluid flow through the Norske Skog Tasman pulp and paper mill, the Carter Holt Harvey pulp mill, and the SCA mill, shown in Figure 19 below.

Figure 19. Secondary use sites at the Kawerau geothermal field [27]

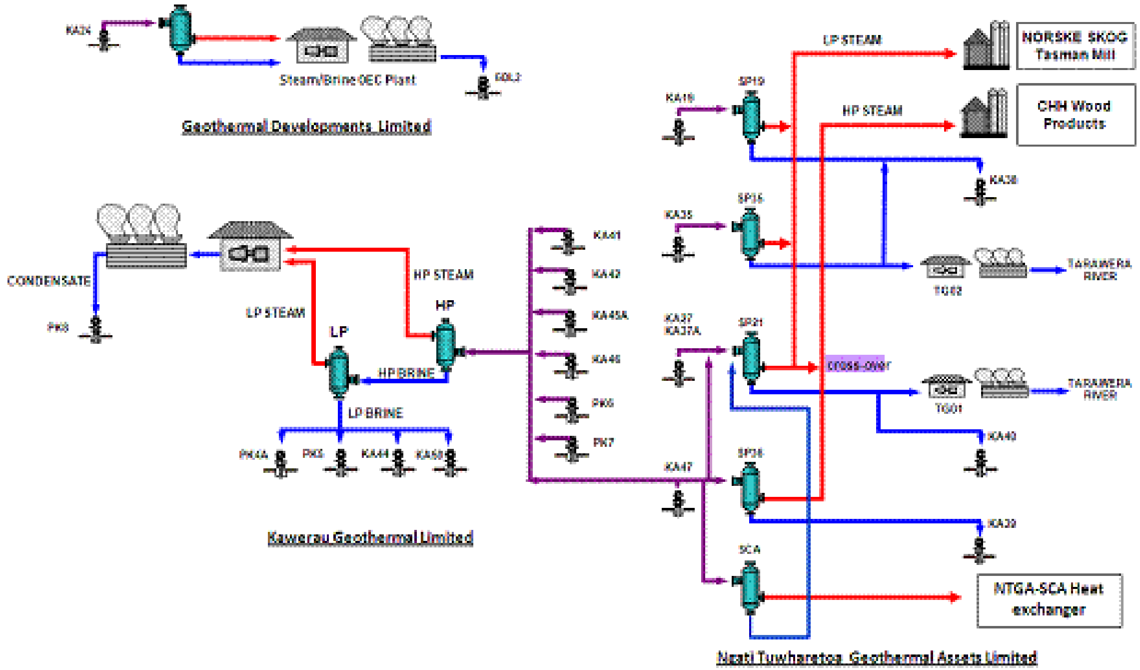
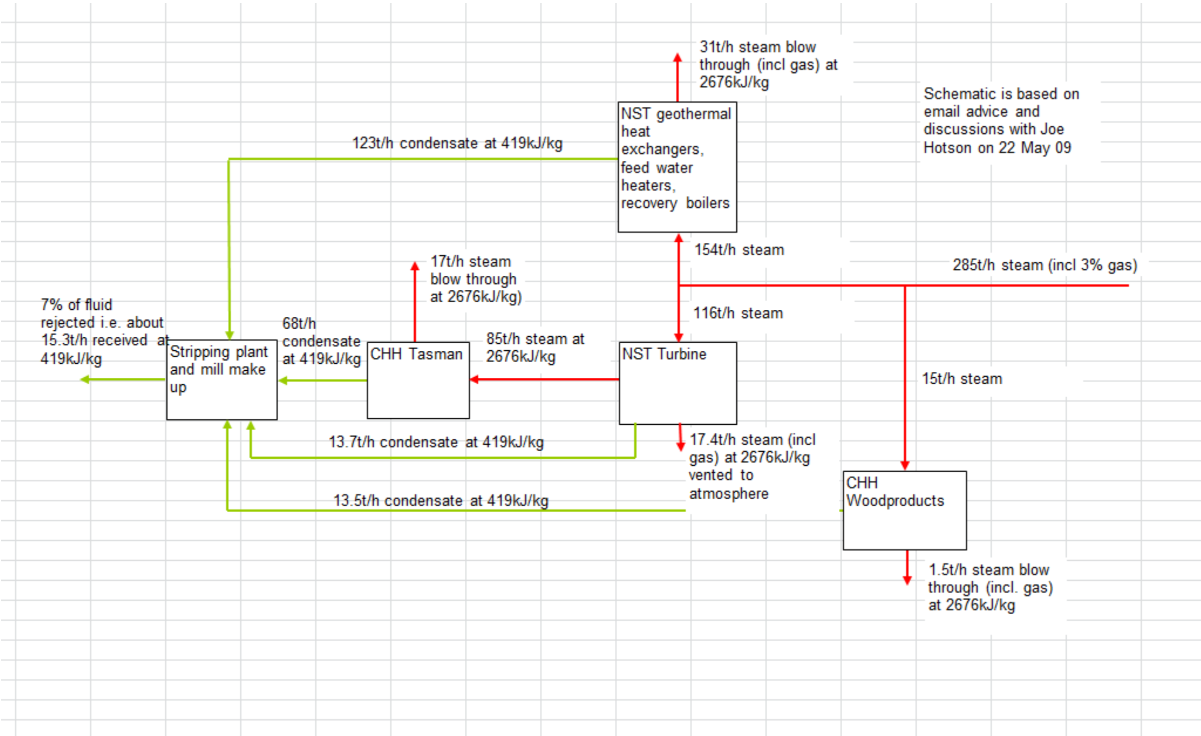


Figure 20 below shows the geothermal fluid flows between these sites connected to the Kawerau geothermal field as well as the data for these flows. This is sourced from the 2014 Geothermal Direct Use Database [33].

Figure 20. Kawerau Secondary Use Diagram [27]



Specific exergy is calculated for total input and total output geothermal fluid, and multiplied by mass data to find total exergy input and output. In this case, the outlet is the discharged and unused geothermal fluid. The difference between input and output is defined as the exergy product.

6.2.4. Efficiency of Geothermal Field Use

Energy and exergy efficiencies were calculated for individual geothermal fields, combining the results from electricity generating sites and secondary use sites. These efficiencies were calculated using Equation 26 below.

Equation 26:

$$\varphi_{field} = \frac{W_e + B^Q}{B_{in} - B_{re-injected}}$$

The variables in this equation correspond to the flows passing through the grey box in Figure 18.

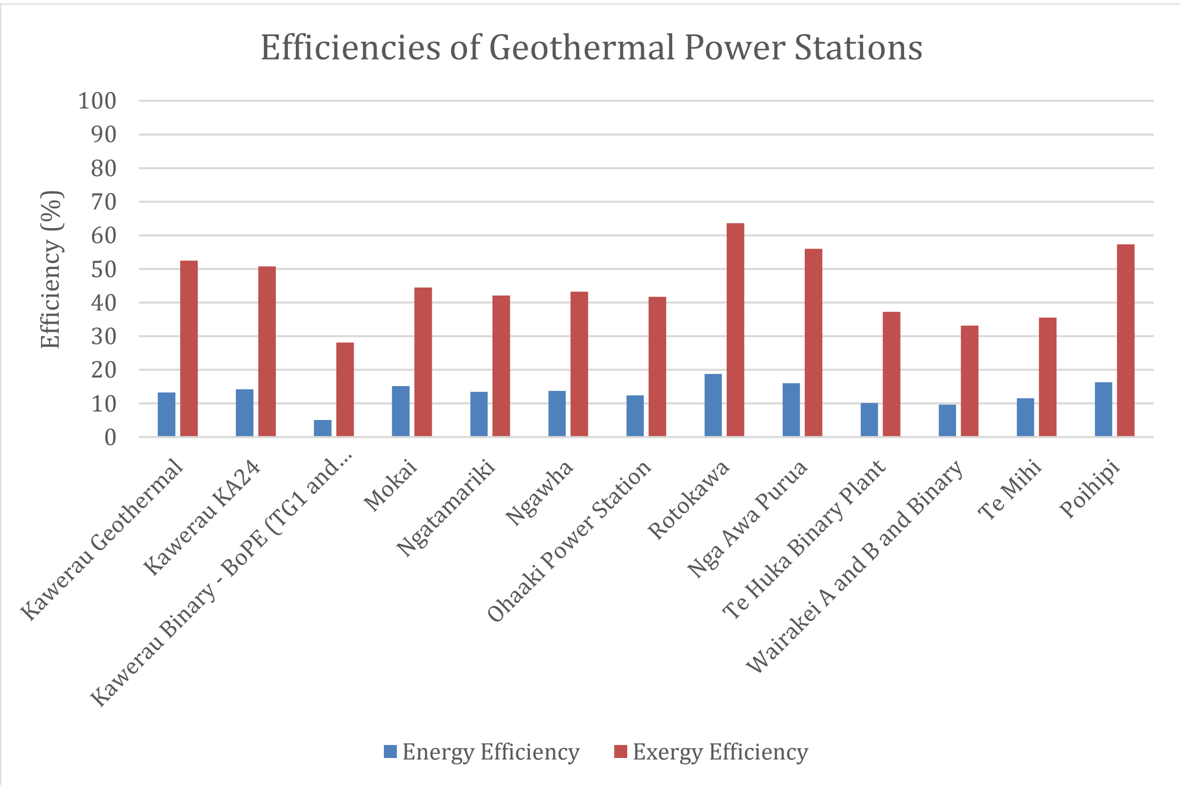
6.3. Geothermal Results and Analysis

6.3.1. Electricity Generation

The energy and exergy efficiencies for individual geothermal power stations are presented below in

Figure 21. A table of these efficiencies are included in Appendix E.1.

Figure 21. Efficiencies for Geothermal Power Stations



These results tend to agree with previous studies. Table 31 includes the efficiencies of power plants that have been sourced from previous exergy studies. These results act as validation for the results from this geothermal exergy analysis.

Table 31. Efficiencies of Geothermal Power Stations from Previous Studies

Power Station	Energy Efficiency (%)	Exergy Efficiency (%)
Kawerau Geothermal Power Plant [51]	13	53
Nga Awa Purua [51]	16	56
Wairakei Power Station [24]	12	45
Poihipi Road Power Station [25]	16	57

Key outliers in Figure 21 include the Rotokawa power station, with much higher efficiencies than any other sites, and Kawerau binary, with the lowest energy and exergy efficiencies. Kawerau Binary is an addition to the Kawerau field, and uses separated fluid from the steam field which supplies Norske Skog Tasman. It should not be assessed by its individual efficiency, rather the increase in efficiency it gives the overall steam field. The Rotokawa power station does not have any clear reason for this high efficiency. Efficiency is dependent on steam quality and the geothermal power plant design. The results suggest that the exergy of the inlet geothermal fluid is small in proportion to the electricity generated, which leads to a high efficiency.

Overall energy and exergy flows for geothermal electricity generation are shown in Table 32. Net input is the total delivered energy or exergy to the electricity generation site, without the separated fluid that is delivered to secondary use.

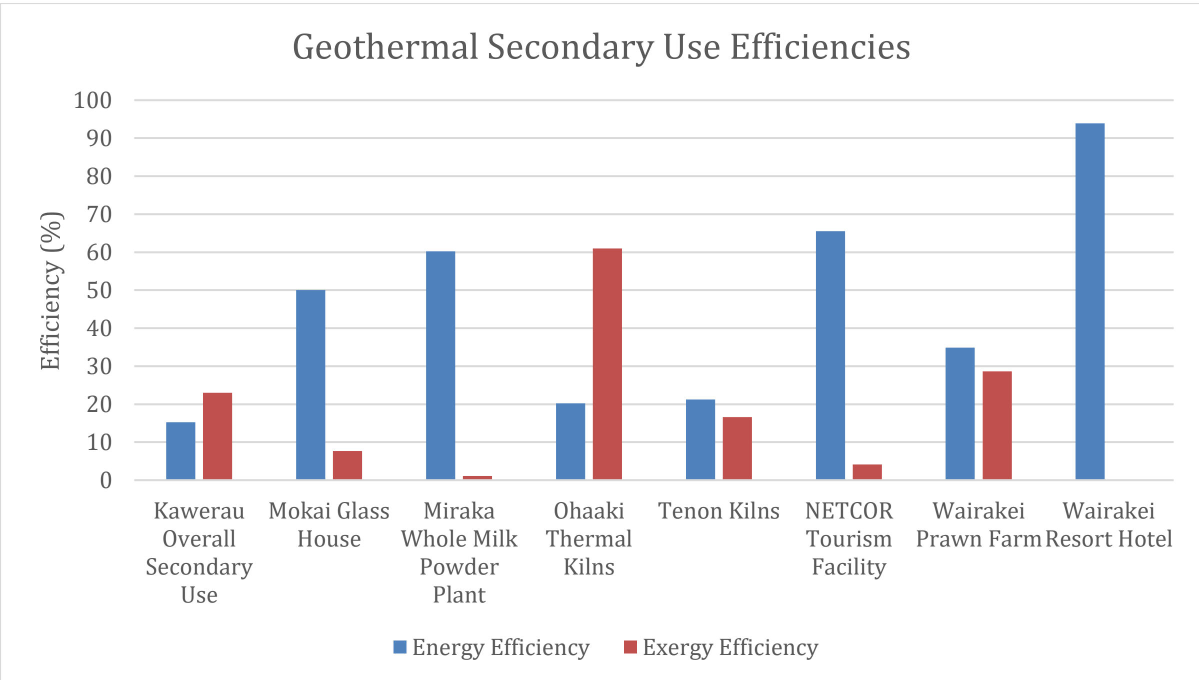
Table 32. Overall Energy and Exergy Flows for Geothermal Electricity Generation

Electricity Generation	Energy	Exergy
Net Input (PJ)	194.8	54.3
Electricity Generated (PJ)	22.9	22.9
Re-injected (PJ)	20.7	2.6
Waste, including rejection (PJ)	151.2	29.2
Efficiency (%)	13	44

6.3.2. Secondary Use

Efficiencies for geothermal secondary use can be seen in Figure 22. The data for this figure can be seen in Table 72 in Appendix E.1. Similar to the results from geothermal power stations, exergy efficiencies are higher than energy efficiencies.

Figure 22. Geothermal Secondary Use Efficiencies



Overall energy and exergy flows for geothermal secondary use are shown in Table 33.

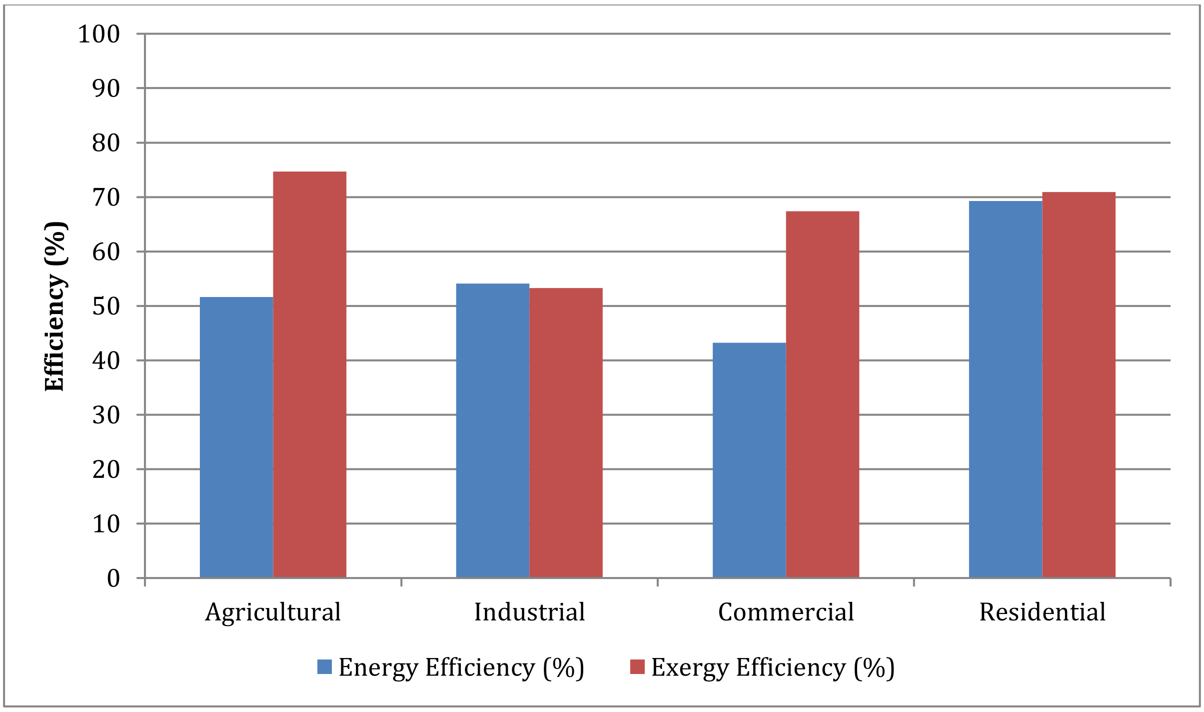
Table 33. Overall Energy and Exergy Flows for Geothermal Secondary Use

Secondary Use	Energy	Exergy
Supply (PJ)	19.5	4.3
Product (PJ)	2.0	3.4
Losses (PJ)	17.5	0.9
Efficiency (%)	10	22

6.3.3. Direct Use

Efficiencies for geothermal direct use are shown in Figure 23. The data for this figure can be seen in Table 73 in Appendix E.1.

Figure 23. Geothermal Direct Use Efficiencies by Sector



There are similarities in the methodology used for direct use and secondary use. Exergy product is calculated as the difference between exergy input and exergy waste, i.e. the calculated exergy product is the maximum possible exergy product from the system, and therefore the exergy efficiency that is calculated is the maximum possible exergy efficiency. In the agricultural, commercial, and residential sectors exergy efficiency appears to be higher than energy efficiency, and the industrial exergy efficiency is slightly lower. This suggests that the industrial processes carried out at these sites do not utilise the full potential of the geothermal resources.

Overall energy and exergy flows for geothermal direct use are shown in Table 34.

Table 34. Overall Energy and Exergy Flows for Geothermal Direct Use

Direct Use	Energy	Exergy
Supply (PJ)	5.2	0.3
Product (PJ)	2.2	0.2
Losses (PJ)	3.0	0.1
Efficiency (%)	42	75

6.3.4. Kawerau Secondary Use System

The exergy and energy flows for the combined Kawerau secondary system is shown in Table 35.

Table 35. Overall Energy and Exergy Flows for Kawerau Secondary Use

Kawerau Secondary Use	Energy	Exergy
Total Inlet (PJ)	14.2	3.6
Total Outlet (PJ)	2.2	0.8
Destruction and Losses (PJ)	12.1	2.8
Efficiency (%)	15	23

6.3.5. National Energy and Exergy Flows

Overall geothermal exergy flows are shown in Figure 24 and Figure 25. Secondary use is represented as a flow from electricity generation, as typically the geothermal fluid inputs to secondary use are the outputs of geothermal power stations. End-use sectors have been combined into a single Direct Use box for this figure, as the flows to each end-use sector is too small to be visible on the diagram when viewed individually. The losses from the electricity generation and cogeneration sectors are much smaller in the exergy diagram than the energy diagram. Exergy analysis assesses the maximum work potential of the geothermal resource. The inlet exergy is much smaller than it appears with energy analysis due to the low quality of the inlet geothermal fluid.

Figure 24. Geothermal Energy Sankey Diagram, 2014

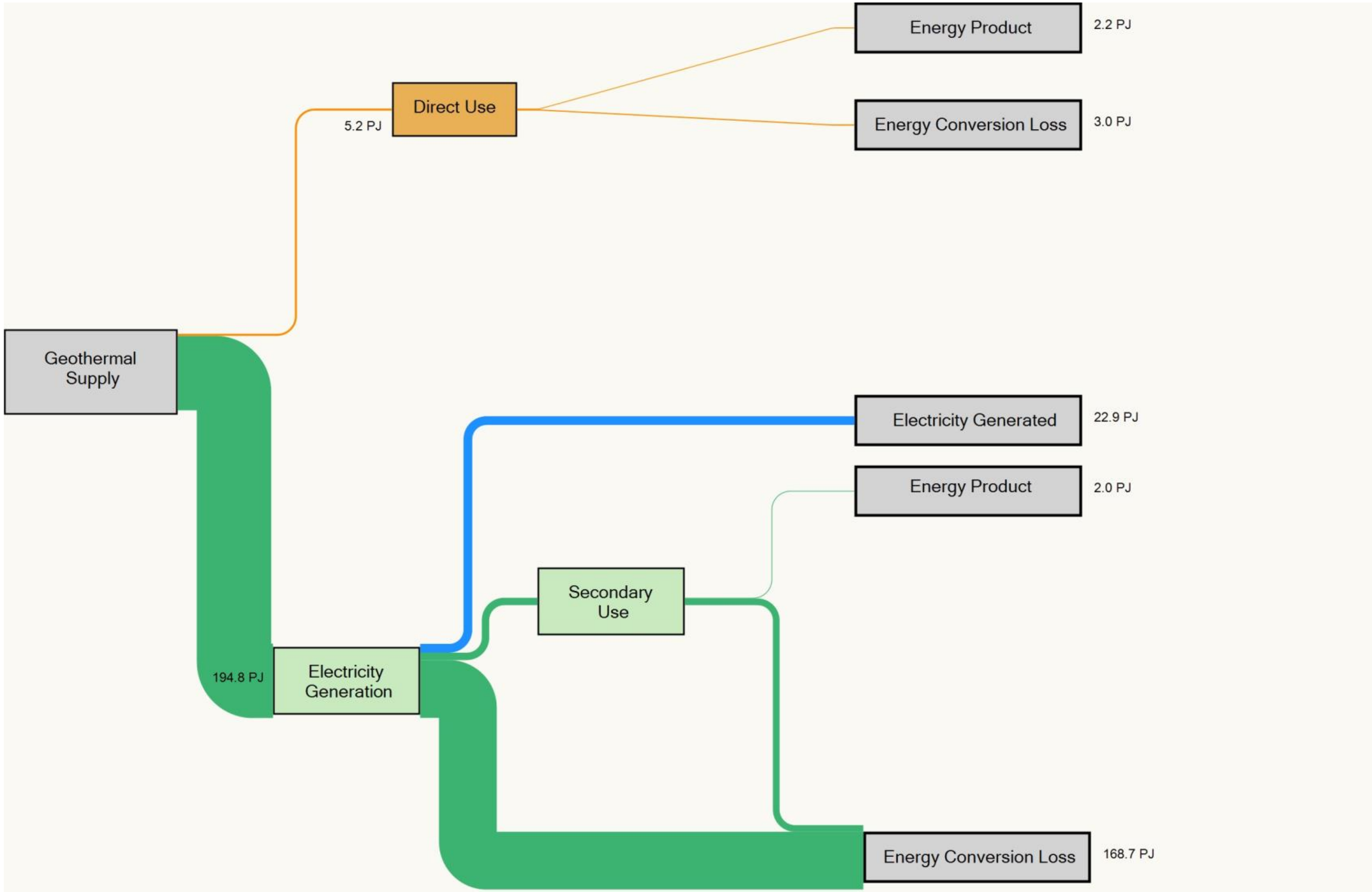
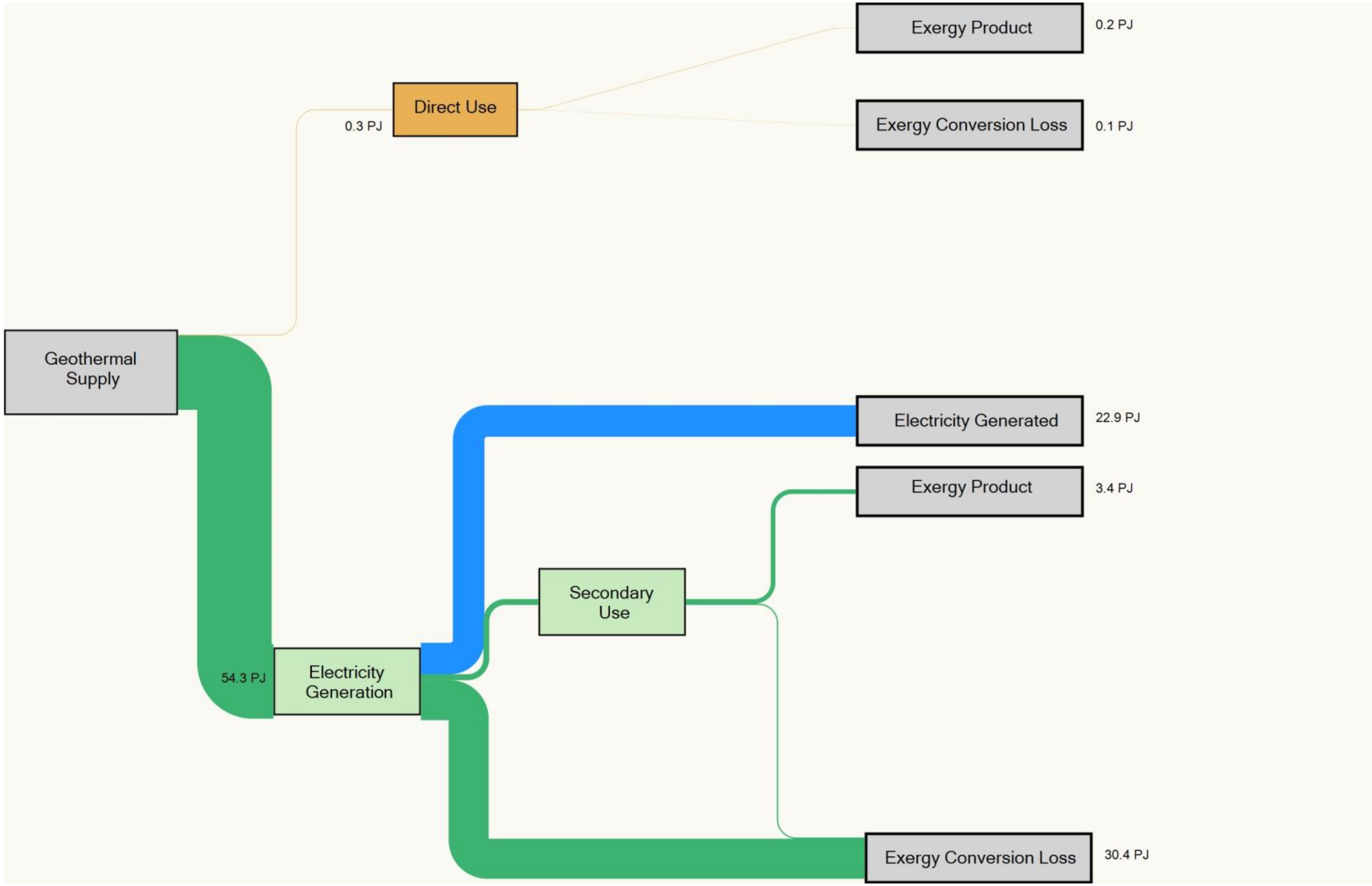


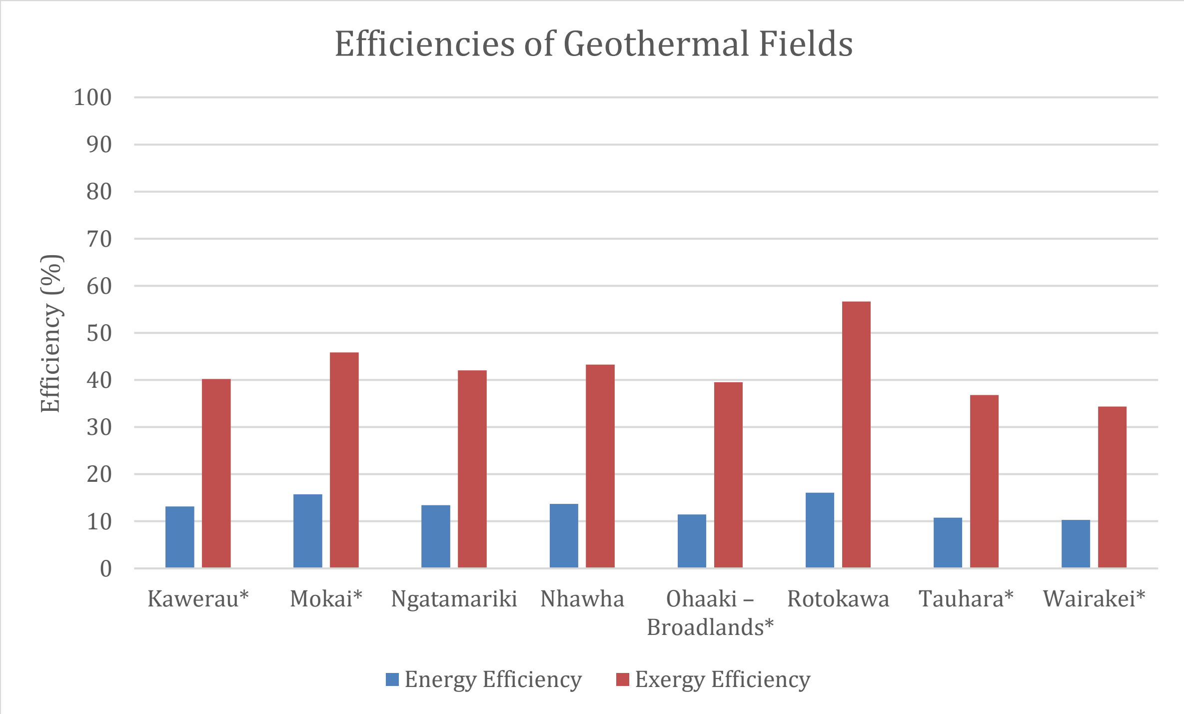
Figure 25. Geothermal Exergy Sankey Diagram, 2014



6.3.6. Efficiency of Geothermal Field Use

The calculated efficiencies of geothermal field use based on Equation 26 are shown in Figure 26.

Figure 26. Geothermal Field Energy and Exergy Efficiencies



Fields that have a secondary use are identified with a *. The list of secondary uses can be seen in Table 30.

6.4. Geothermal Discussion

These results show that energy analysis does not give a true representation of the geothermal systems. In general, exergy efficiencies are all higher than energy efficiencies. Energy analysis doesn't account for fuel quality so the energy potential of the input geothermal fluid appears to be greater than it is. Energy efficiencies are low because only a small amount of electricity is generated, or there is a small energy product, which results from a proportionally large energy input. Exergy inputs are much smaller than energy inputs, as the quality (i.e. the potential for work generation) of the low temperature geothermal steam is now accounted for. The electricity or exergy products are higher compared to the reduced exergy input, and therefore the calculated exergy efficiencies are higher. This is the case for the overall field analysis presented in Figure 26, and is also a consistent theme with individual power stations, secondary uses and direct uses. The exergy efficiency is just a more accurate representation of the geothermal plant efficiency than the energy efficiency.

This analysis gives a general idea of how an exergy analysis can affect our understanding of the geothermal energy system. Exergy analysis is important for New Zealand especially because so much of the national energy supply is from geothermal resources. The misunderstandings that come from using an energy analysis have a large impact on the overall understanding of New Zealand's energy system. This is discussed further in section 11.2. of this report.

7. Biomass and Biofuels

7.1. Biomass and Biofuel Use in New Zealand

Four types of biofuels are produced and used in New Zealand: biogas, woody biomass, black liquor and liquid biofuels.

Currently most of New Zealand's biogas is created from digesting waste at wastewater treatment plants and landfills [17]. Additional sources include rural organic residues and food processing organic residues [65]. The biogas is consumed in electricity generation and cogeneration processes, which are listed in Appendix A.1.

Woody biomass mostly includes Pinus Radiata wood waste in the form of bark, chip fines and some sawdust [66]. It is consumed at a number of cogeneration plants located at wood processing factories [17], which are listed in Appendix A.1.

Black liquor is the spent cooking liquor from the Kraft pulp production process when digesting pulpwood into paper pulp by removing lignin, hemicelluloses and other extractives from the wood to free the cellulose fibres [66]. This by-product fuels black liquor recovery boilers, which is produces heat for industrial end-use processes.

Almost all liquid biofuel production in New Zealand is blended with fossil fuel oil products and so, by IEA definition, it is consumed by the oil products sector and is included in oil product statistics [15]. Liquid biofuels are approximated to ethanol [67].

7.2. Biomass and Biofuels Analysis

7.2.1. Biofuels Physical and Chemical Data

Composition data was found for each biofuel type; biogas, woody biomass and black liquor.

1. *Biogas*

Due to the natural variation in biogas composition, a general composition for natural gas was used to for biogas calculations.

Table 36. Biogas mass fraction data [31]

General Biogas Composition	Mass Fraction (%)
Carbon	68
Hydrogen	22
Oxygen	0
Nitrogen	10
Sulphur	0

The ϕ value for biogas is 1.04, calculated from Equation 15 and the above composition data.

2. *Woody Biomass*

Woody biomass is approximated as Pinus Radiata [66].

Table 37. Woody biomass DAF mass fraction data [31]

General Woody Biomass Composition	Mass Fraction (%)
Carbon	42.6
Hydrogen	5.2
Oxygen	36.6
Nitrogen	0.1
Sulphur	0
Water	15
Ash	0.5

The ϕ value for woody biomass is 1.12 [31].

3. *Black Liquor*

Composition data for black liquor is provided below.

Table 38. Black liquor mole fraction data [68]

General Black Liquor Composition	Mole Fraction (%)
H	3.3
H_2O	39.6
C	18.8
O	16.3
Na_2CO_3	4.2
NaOH	11.5
Na_2S	7.2

The ϕ value for black liquor is 0.62 [68].

4. *Liquid Biofuels*

Liquid biofuels are approximated to ethanol. Data for liquid biofuels is provided in Table 39, sourced from [69].

The ϕ values for each biofuel type are multiplied by NCVs, according to Equation 10, to find specific exergy values, shown in Table 39.

Table 39. Specific exergy calculation data for biofuels

	Biogas	Woody Biomass	Black Liquor	Liquid Biofuels
ϕ	1.04	1.12	0.92	1.02
NCV (kJ/kg)	28034	19200	8600	28865 [69]
Specific Exergy (kJ/kg)	29155	17641	7954	29532 [69]

Total delivered exergy is calculated from specific exergy and delivered mass. The mass data supplied by MBIE is for biomass and black liquor that still contains moisture. This data is converted to dry mass using moisture contents coals in order to calculate exergy values. Moisture contents for woody biomass and black liquor are shown in Table 40 below. This table also includes the calorific values for these fuel types. The GCV for woody biomass is taken as the GCV for fresh harvester wood, and the NCV is that of oven-dried wood.

Table 40. Moisture content and calorific values for woody biomass and black liquor [15]

Moisture Content Calculations	Woody Biomass	Black Liquor
Moisture content (%)	0.5	0.5
NCV (kJ/kg)	19200	8600
GCV (kJ/kg)	9300	10500

7.2.2. Electricity Generation

In New Zealand, only biogas is consumed for electricity generation. Exergy input is calculated from the multiplication of biogas specific exergy and the volume of biogas delivered to Electricity Generation from MBIE data tables [15]. Exergy output is the electricity generated, which is sourced from the MBIE Electricity Data Table [15].

7.2.3. End Use

Biogas, woody biomass, black liquor and liquid biofuels are all consumed in the end-use sector. Equation 2 is used to calculate end-use products for heat processes, and non-heat products are calculated using the efficiencies in Table 7. Exergy products and conversion losses were calculated for each end-use process. Liquid biofuels are consumed within the end-use sector as an oil product. These have been included within the oil analysis in Chapter 4.

7.2.4. Cogeneration

Biogas and woody biomass are both utilised in cogeneration systems in New Zealand. MBIE provide data on biogas and woody biomass delivered to cogeneration sites, and the electricity that is generated. The value of the heat product is unknown, so typical plant efficiencies are used in this analysis to approximate the heat product from the cogeneration system.

7.2. Biomass and Biofuels Results

7.2.2. Electricity Generation

Energy and exergy flows for electricity generation from biogas are presented in Table 41.

Table 41. Electricity generation calculations for biogas

Electricity Generation	Energy	Exergy
Input (PJ)	2.0	2.0
Output (PJ)	0.8	0.8
Conversion Loss (PJ)	1.2	1.2
Efficiency (%)	41	39

7.2.3. End-Use

The end-use results for biogas, woody biomass and black liquor are aggregated in Table 42 below.

Table 42. Biogas end-use calculations by sector

Sector	Delivered Energy (TJ)	End Use Energy (TJ)	Energy Efficiency (%)	Energy Conversion Loss (TJ)	Exergy Efficiency (%)	Delivered Exergy (TJ)	End Use Exergy (TJ)	Exergy Conversion Loss (TJ)
Agricultural	7	6	85	1	11	7	1	6
Commercial	254	216	85	38	12	264	32	232
Industrial	38566	25549	66	13017	29	47863	13968	33895
Residential	6256	1974	32	4281	1	10714	82	10632
Transport	0	0	0	0	0	0	0	0
Total	45082	27745	62	17337	24	58848	14084	44765

7.2.4. Cogeneration

Values for calculating energy and exergy efficiencies and conversion losses for cogeneration from biogas are shown below in Table 43.

Table 43. Biogas cogeneration calculations

Biogas Cogeneration	Energy	Exergy
Input (PJ)	0.7	0.8
Product Output (PJ)	0.6	0.4
Electricity Output (PJ)	0.0	0.0
Total Output (PJ)	0.6	0.4
Conversion Loss (PJ)	0.1	0.4
Efficiency (%)	85	52

Values for calculating energy and exergy efficiencies and conversion losses for cogeneration from woody biomass are shown below in Table 44.

Table 44. Woody biomass cogeneration calculations

Woody Biomass Cogeneration	Energy	Exergy
Input (PJ)	4.3	7.3
Product Output (PJ)	1.2	0.4
Electricity Output (PJ)	1.3	1.3
Total Output (PJ)	2.5	1.7
Conversion Loss (PJ)	1.5	5.3
Efficiency (%)	62	24

7.2.5. National Energy and Exergy Flows

Each of the fuel consumption processes can be seen in the form of Sankey diagrams in Figure 27 and Figure 27. The Sankey diagrams for each of biogas, woody biomass and black liquor have been presented in one figure so that the flows can be compared between each resource. This gives an indication of the scale of energy provided by each resource in New Zealand. This figure shows that biofuels consumption in New Zealand is dominated by woody biomass use in end-use processes. A large amount of black liquor is also consumed in end-use processes. As small amount of biogas is utilised in the agricultural and industrial end-use sectors, but these are so small that they cannot be seen clearly in the figure.

Figure 27. Biofuels Energy Sankey Diagram, 2014

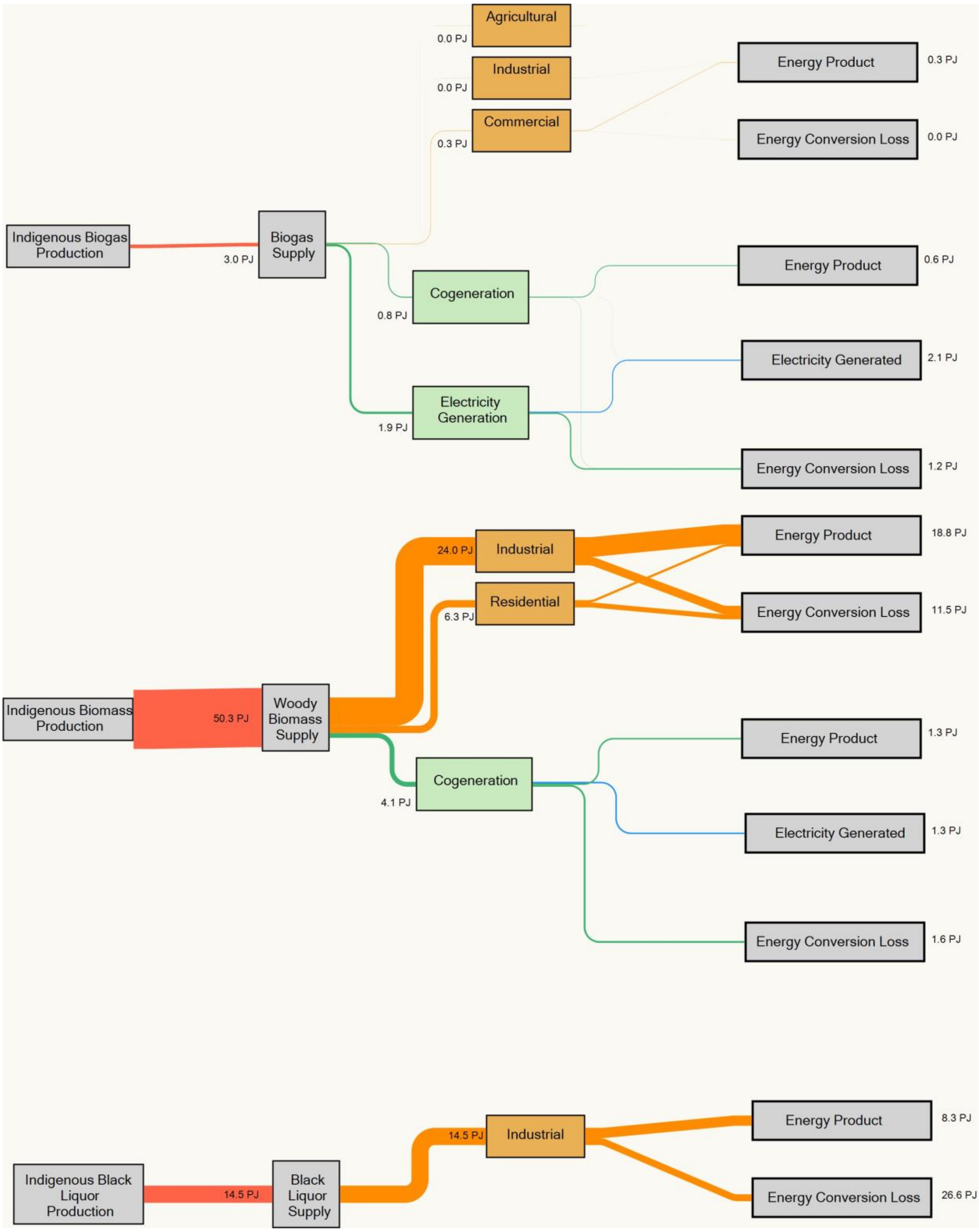
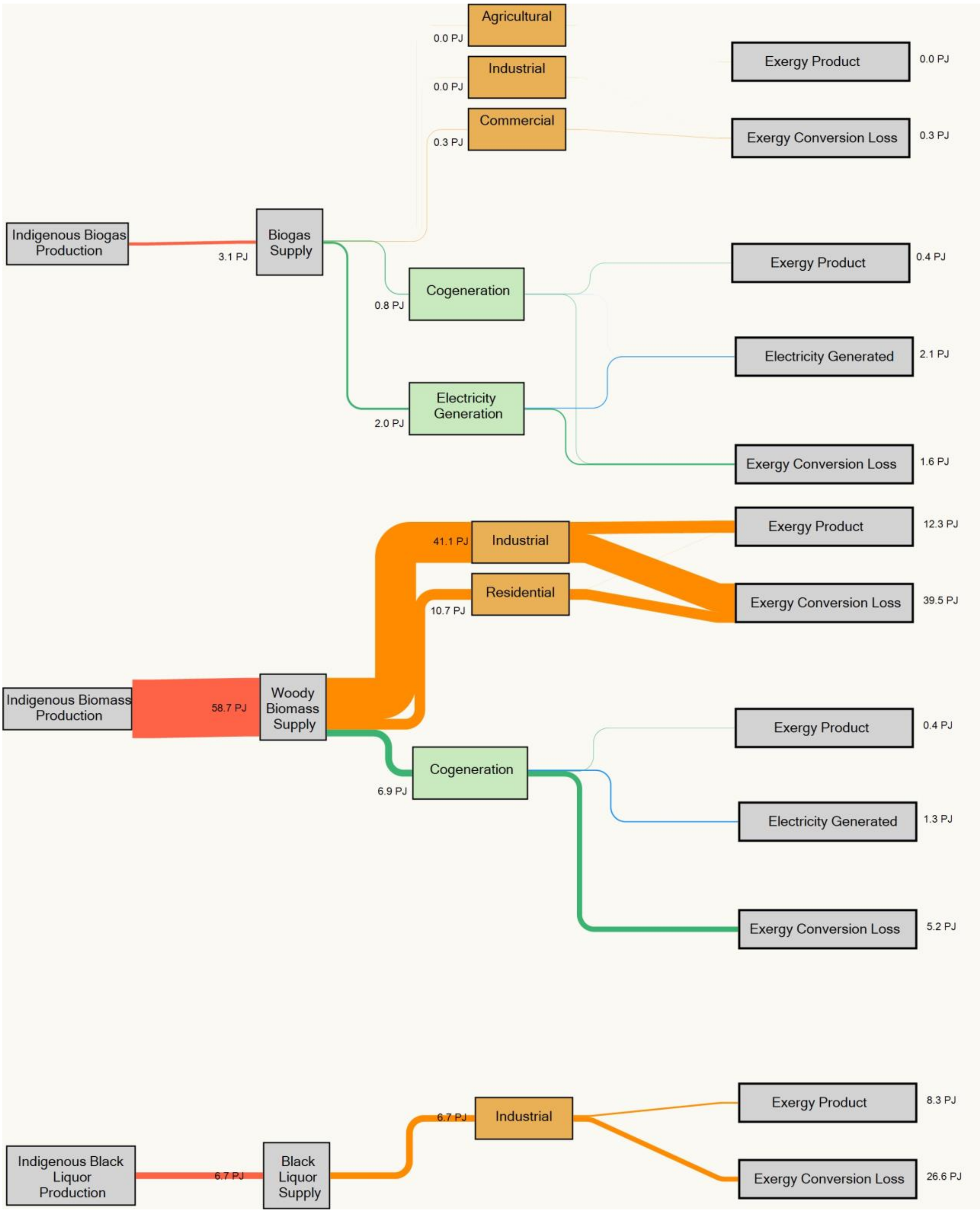


Figure 28. Biofuels Exergy Sankey Diagram, 2014



7.3. Biomass and Biofuels Discussion

Overall energy and exergy efficiencies for each transformation process and end-use sector are shown in Table 45.

Table 45. Energy and exergy efficiencies for the biofuels sector

	Energy Efficiency (%)	Exergy Efficiency (%)
Biogas		
Electricity Generation	41	39
Cogeneration	85	52
Agricultural Sector	85	11
Industrial Sector	85	11
Commercial Sector	85	12
Woody Biomass		
Cogeneration	62	24
Industrial Sector	70	30
Residential Sector	32	1
Black Liquor		
Industrial Sector	60	26

Exergy efficiency is lower than energy efficiency in all sectors. Electricity generation, cogeneration and high temperature industrial processes have the highest exergy efficiencies, similar to the results of other fuels. An energy analysis suggests that biogas consumption in the end-use sectors is the most efficient use of biogas, whereas from an exergy analysis we can see that electricity generation and cogeneration are more efficient and have fewer losses. The woody biomass processes in the industrial sector are the most efficient use of this resource, while those in the residential sector are very inefficient. It is important to consider that many of these resources are waste products that are creating a useful product that would otherwise be lost. This is particularly true for black liquor consumption, which is a high value by-product of pulp processing.

8. Other Renewables

8.1. Other Renewables in New Zealand

80% of New Zealand's electricity generation came from renewable energy resources in 2014, which includes hydropower, geothermal, biogas, wood, wind and solar [15]. The Government's Energy Strategy aims to lift this to 90 per cent by 2025 [46]. This chapter focuses on the additional renewable resources not previously mentioned, including hydropower, wind and solar. Hydropower is the largest source of electricity for New Zealand, providing 57% of total electricity generation in 2014. Wind and solar have been increasing developed in New Zealand, and currently supply 5% and 0.04% respectively. The proportions of electricity generation from all resources in New Zealand can be seen in Figure 3.

Solar is also used for low temperature water heating in the residential sector. Any small-scale hydro and wind end use are not included in this analysis as they are too small to have a noticeable impact on the overall analysis and do not appear in the EECA end-use database.

8.2. Other Renewables Results

Energy and exergy inputs and products for Other Renewables electricity generation can be seen in Table 46.

Table 46. Other Renewables electricity generation calculations.

Utility	Hydro	Wind	Solar
Delivered Energy (PJ)	87.6	8.0	0.1
Energy Product (PJ)	86.7	7.9	0.1
Energy Losses (PJ)	0.9	0.1	0.0
Delivered Exergy (PJ)	87.6	8.0	0.1
Exergy Product (PJ)	86.7	7.9	0.1
Exergy Losses (PJ)	0.9	0.1	0.0
Energy Efficiency (%)	99	99	100
Exergy Efficiency (%)	99	99	100

Exergy results are the same as energy results due to the assumptions made in this exergy analysis about energy and exergy inputs. This analysis is heavily dependent on the energy efficiency of the renewable resources that are determined by MBIE, as the energy and exergy products, as well as the exergy efficiency, are all calculated using this energy efficiency.

Hydropower dominates electricity generation, generating 10 times the electricity of wind and solar combined. It is an efficient way to generate a large amount of electricity, which is a pure exergy product. The maximum work potential of electricity is the same as its energy potential. Electricity can also be utilised by a range of end-use and transformation processes.

Energy and exergy efficiencies for solar water heating can be seen in Table 47.

Table 47. Solar end-use energy and exergy efficiencies

Sector	End Use	Technology	Energy Efficiency (%)	Exergy Efficiency (%)
Residential	Low Temperature Heat (<100 C), Water Heating	Hot Water Cylinder	94	13

Exergy efficiency of solar direct use is much lower than energy efficiency due to the low temperature output which is heated water. If solar energy were a finite resource, this would suggest that utilising solar for electricity generation would result in fewer exergetic losses than using it for water heating, and that an alternative resource should be used for water heating, but solar exposure is a free resource which cannot be depleted by consumption. The work potential from solar depends on the technology that is there to capture it. This suggest that if it is feasible to install a solar water heating system based on the external limitations (such as economics and geographical limitations) that would appear in an energy analysis, this installation would also be feasible in terms of an exergy analysis.

From this analysis, it appears that renewables are highly efficient at capturing high quality exergy, but it is important that this result is dependent on many assumptions. The energy and exergy efficiencies for hydro, wind and solar should not be compared to other resource efficiencies, as they have been calculated under different assumptions. The usefulness of the current analysis is to provide an indication of size of flows of energy and exergy flows association with these renewables through the New Zealand energy system, and how these compare to other resources.

Renewable resources such as these can capture a free resource that is readily available. There are similar arguments for renewables based on an exergy analysis as would be found in an energy analysis, because the results of an energy analysis of renewables systems are essentially the same as those of an exergy analysis. These arguments for renewables include a readily available resource with minimal impact on the environment, while arguments against include complexities with seasonal and daily variation leading to fluctuations in electricity generation.

9. Waste Heat

9.1. Waste Heat in New Zealand

Some industrial processes, e.g. fertiliser production, are exothermic, meaning that the chemical reactions generate heat as a by-product. The waste heat is captured and used to generate electricity. In New Zealand, 0.19PJ of electricity was generated from waste heat in 2014 [15]. The waste heat generation processes are different from cogeneration, as the heat product is not a result of the energy input that is driving the industrial processes, but is due to the exothermic reaction between materials. The energy and exergy products come from material inputs which have been excluded from this national exergy analysis. This means that energy and exergy inputs are estimated. The energy input to waste heat electricity generation is estimated by MBIE using a 15% electrical transformation factor [17]. This will be used as a framework for the exergy analysis. A total chemical exergy analysis could be carried out on the exergy inputs that drive the waste heat production, but this scale of analysis is beyond the scope of this thesis.

9.2. Waste Heat Methodology

The methodology for exergy analysis of waste heat electricity generation is based on the assumptions made by MBIE. The energy input is estimated from electricity generation data using a 15% efficiency. An exergetic temperature factor is calculated from approximate process temperatures, using Equation 17. The environmental temperature is the average New Zealand temperature, and the process temperature is the typical temperature for the Haber process, which is the main industrial procedure for ammonia production [70]. The exergetic temperature factor is multiplied by the energy efficiency to get an approximate exergy efficiency. An exergy input can then be calculated from exergy efficiency and exergy product which is the electricity generation. Energy and electricity data are sourced from the "Electricity" and "Renewables" MBIE data tables [15].

Table 48. Assumed values for waste heat calculations

Waste Heat Values	Value
Environmental Temperature (K)	288.2
Process Temperature (K)	773.2
Exergetic Temperature Factor	0.6

9.3. Waste Heat Results and Analysis

Energy and exergy inputs and products are shown below in Table 49. Exergy efficiency is higher than energy efficiency, due to the smaller exergy input value that was calculated from the exergetic temperature factor.

Table 49. Electricity generation calculations for waste heat.

Electricity Generation	Energy	Exergy
Input (PJ)	1.3	0.8
Electricity Output (PJ)	0.2	0.2
Conversion Loss (PJ)	1.1	0.6
Efficiency (%)	15	24

The results suggest that the exergy content of waste heat is lower than the energy content. The maximum work potential of the waste heat is dependent on the temperature conditions of the waste heat compared to the environmental conditions. When these conditions are accounted for, the potential for waste heat to do work appears to be reduced.

There are few changes that could be made to reduce exergetic losses when generating electricity from waste heat. The key changes are to improve the energy efficiency of the generating system, and increase the processes temperature. Both bits of data are approximated in this analysis, and there is not enough information about the fertiliser processes in New Zealand to advise improvements to the current processes. It could be an interesting study to look into this in more detail with accurate temperature and energy efficiency data, as well as calculating each of the chemical exergy inputs and outputs of the exothermic reaction, but this is beyond the scope of this project. The electricity being produced from the waste heat is an increase in site efficiency, and an improvement to New Zealand's overall energy system. The key insight that the exergy analysis of waste heat electricity generation provides is the part that it plays in the entire New Zealand energy and exergy analysis.

10. Overall Results

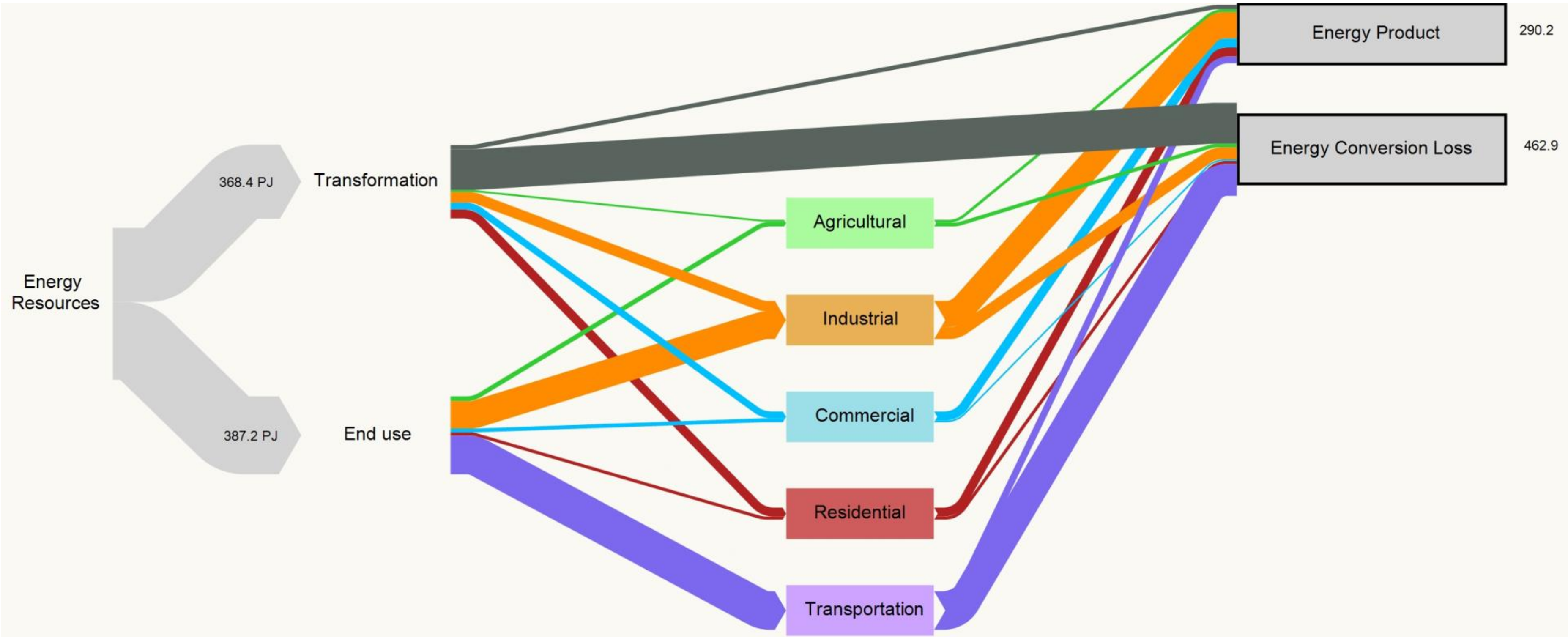
This chapter combines the results and analysis for each of the resources described in the previous chapters to form a description of the New Zealand energy system based on an exergy perspective.

Inputs, products, and losses from each resource are combined for transformation processes and end-use processes, and are presented in Figure 29 and Figure 31 in New Zealand Energy and Exergy Flow Sankey Diagrams. These give a visualisation of the energy and exergy provided to each method of consumption, as well as the proportion of this that it utilised to form an energy or exergy product, and that which is lost. Each diagram has individual points that can aid our understanding of the New Zealand energy system, but key discoveries are found when the two figures are compared to each other.

10.1. Overall Energy Results

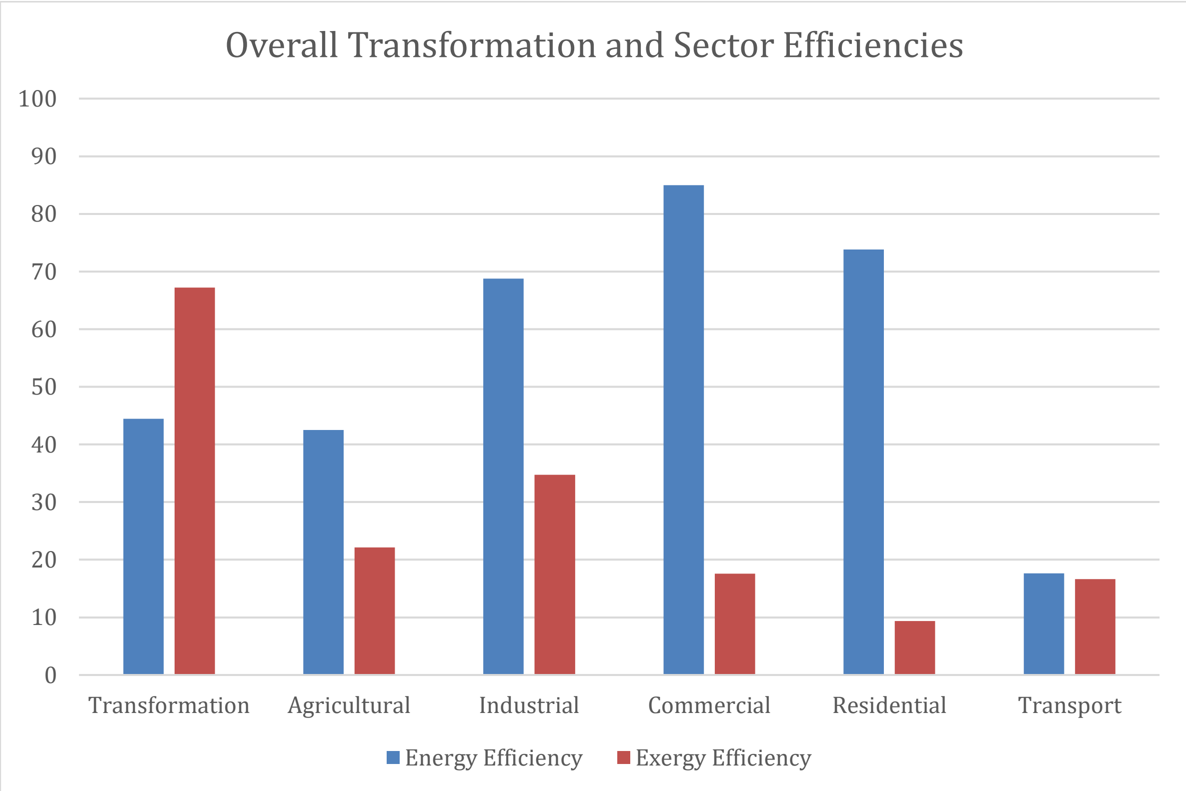
The New Zealand energy system, analysed from an energy perspective, can be seen below in Figure 29. This is the result of the energy analyses which were carried out for each resource, and which have been combined into an overall energy analysis for New Zealand.

Figure 29. Energy Flow through New Zealand (PJ), 2014



This figure provides a visualisation of the massive losses from the transformation and transport sectors, which are particularly impactful when compared with the small amount of energy product from these sectors. Energy analysis highlights these sectors as being the most suitable for efficiency improvements. The energy efficiencies for each end-use sector and the transformation sector are included in Figure 30.

Figure 30. Overall energy and exergy efficiencies for transformation processes and sectors



The supporting data for this figure can be found in Appendix G.2.

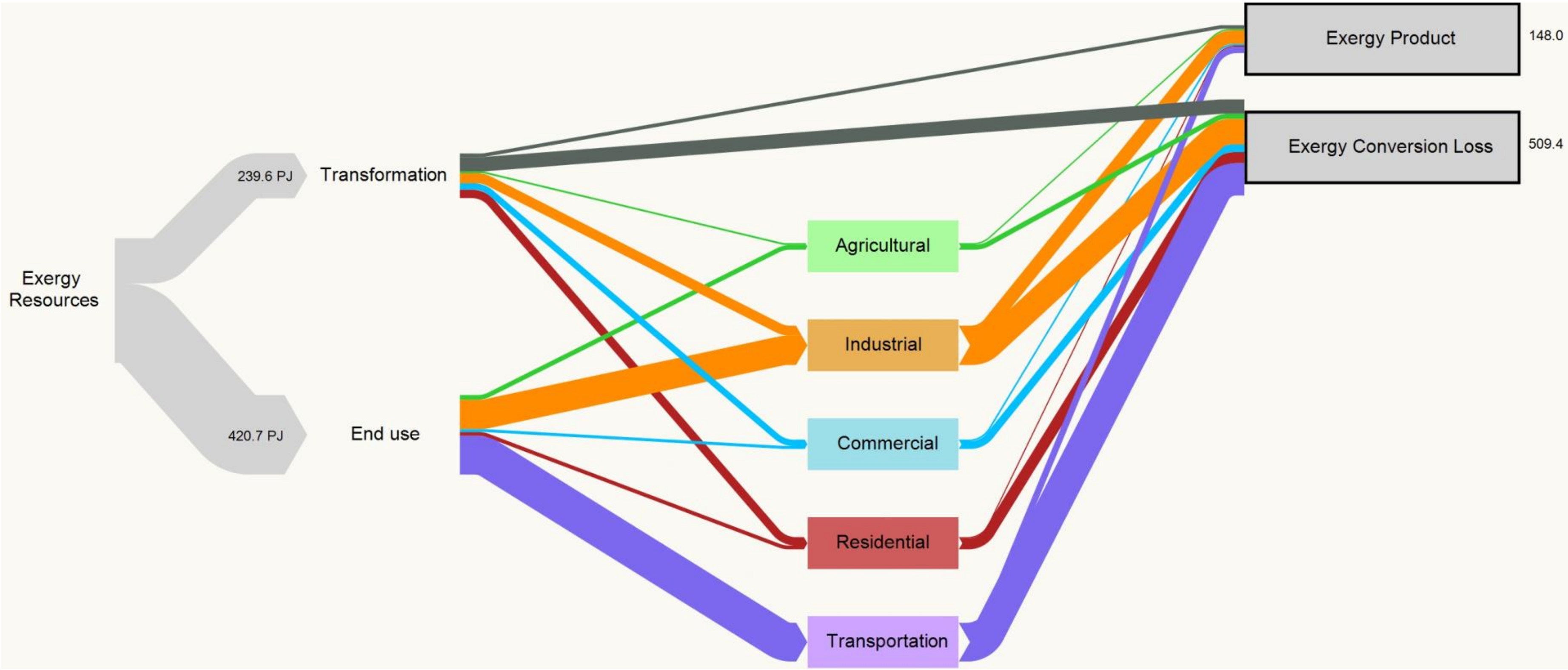
The commercial, residential and industrial sectors are the most energy efficient. Transport performs much worse than any of the other sectors, at 18% energy efficiency. According to an energy analysis, improvements should be made in the transport sector, as well as transformation and agricultural sectors.

New Zealand has an overall energy efficiency of 38%. This is lower than other countries, which range between 39-60%, due to the large amount of geothermal electricity generation that occurs in New Zealand. As discussed previously, geothermal power stations appear to be very energy inefficient under an energy analysis, and this brings down the overall energy efficiency of the country.

10.2. Overall Exergy Results

The New Zealand exergy system, analysed from an exergy perspective, is shown in Figure 31 below. This is the result of the exergy analyses which were carried out for each resource, and which have been combined into an overall exergy analysis for New Zealand.

Figure 31. Exergy Flow through New Zealand (PJ), 2014



Overall exergy efficiency of New Zealand is 22%, which is lower than the overall energy efficiency at 38%. This can be seen in above Sankey diagrams as the overall exergy product in Figure 31 is much smaller in proportion to the losses than the energy product is in Figure 29. In terms of scale, there are massive losses within the transport sector, which is in agreement with the results of the energy analysis. There are also major losses from the industrial sector, but more importantly the residential and commercial sectors have large loss in proportion to their exergy products. The exergy efficiencies of each sector are shown in Figure 30, and highlight areas where exergy potential is being lost.

Exergy efficiencies are all lower than energy efficiencies, except for in the transformation sector where there are geothermal power stations. Low exergy efficiencies indicate that the resources are not being utilised to their maximum potential. The residential and commercial sectors are some of the poorest performers in an exergy analysis, while the energy analysis shows them as the most efficient. This highlights how energy analyses can fail to describe an energy system. The residential and commercial sectors are dominated by low temperature space and water heating processes, which are inefficient from an exergy viewpoint due to the low-quality heat output.

New Zealand's overall exergy efficiency is much lower than its overall energy efficiency, but this should not be observed as an isolated conclusion. All countries have lower exergy efficiencies, which range between 15-39%.

11. Discussion

11.1. The Impact of Geothermal Systems

The major difference between national energy (Figure 29) and exergy (Figure 31) flows occurs at the Transformation processes. This is due to geothermal systems. The delivered geothermal energy to transformation is much higher than the delivered geothermal exergy, and so the energy losses are much greater than the exergy losses. The reasons for this have been discussed in detail in section 6.3., and are essentially that the electricity generation potential of the geothermal steam is accounted for with exergy analysis, but not by energy analysis. The difference between these figures gives an idea of the scale of the impact that geothermal sector has on our understanding of the New Zealand energy system. Geothermal is responsible for 26% of New Zealand's Total Primary Energy Supply (TPES). When analysed using exergy, it is 9% of the Total Primary Exergy Supply (TPExS). This can be seen in Figure 32 and Figure 33 below.

Figure 32. Total Primary Energy Supply by Resource, 2014 [15]

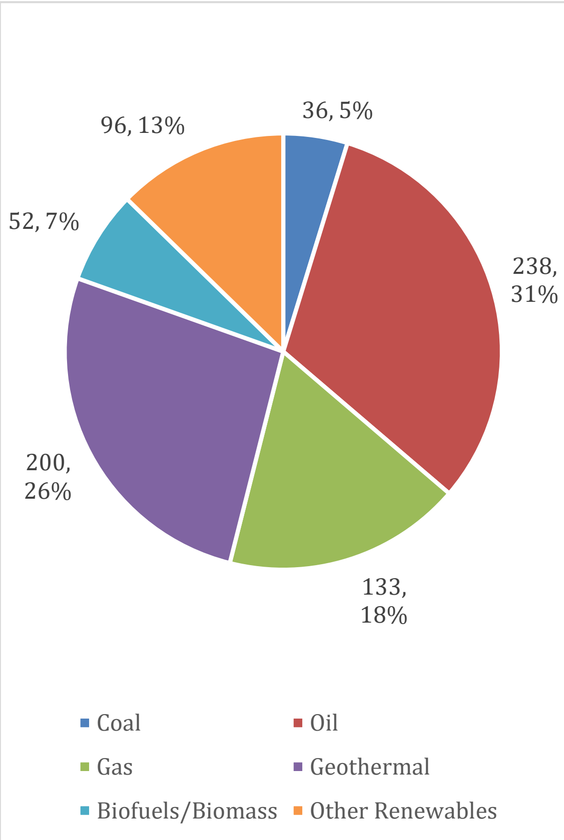
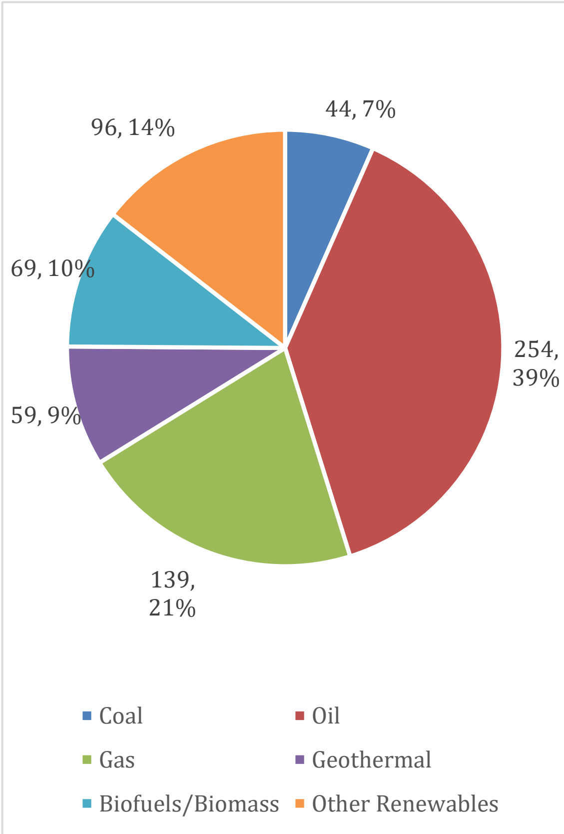


Figure 33. Total Primary Exergy Supply by Resource, 2014

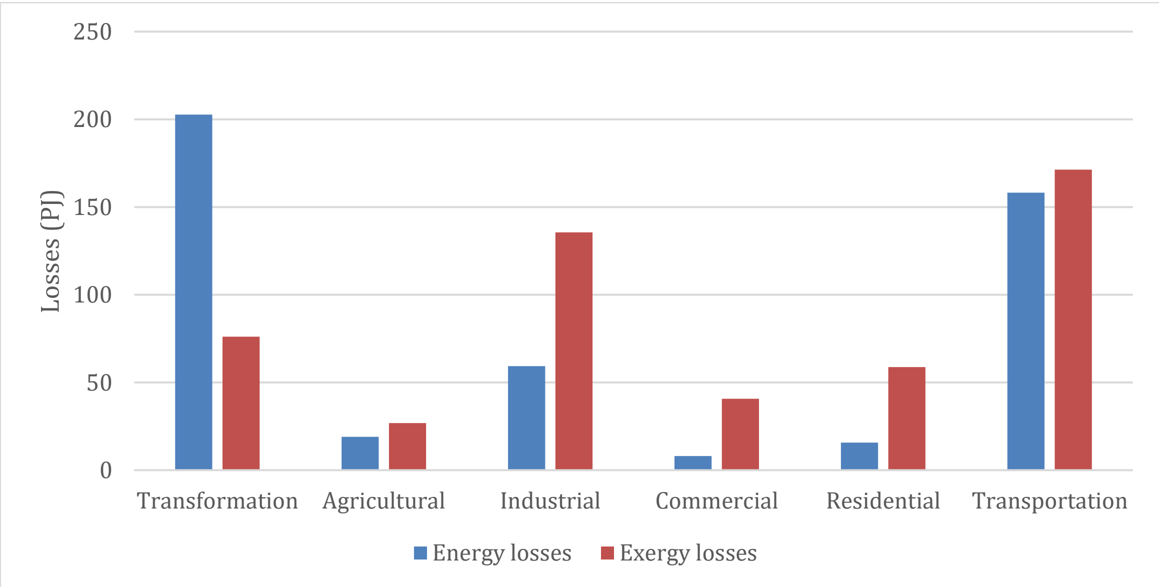


Not only is the proportion of geothermal energy supply distorted, but also the proportions of each resource in relation to this. According to energy analysis, oil contributed to 31% of our primary energy supply, but with exergy analysis this is much higher at 39%. This distorts our understanding of the use of geothermal fuel in New Zealand, and also the overall energy resource use. For many countries, this is not an issue as they have little or no geothermal resource utilisation in their energy supply. Geothermal is responsible for a large proportion of energy supply in New Zealand so it has a major impact on the overall understanding of the country's energy system.

11.2. Waste and Losses

Exergy losses offer a quite different perspective on energy system performance and offer an alternative analytical basis to indicate areas for improvement. Areas with low efficiency and high resource use will have the highest losses, and are therefore the areas that should be prioritised for improvement. Energy and exergy losses from the transformation sector and each end-use sector are summarised in Figure 34.

Figure 34. Energy and exergy losses by sector

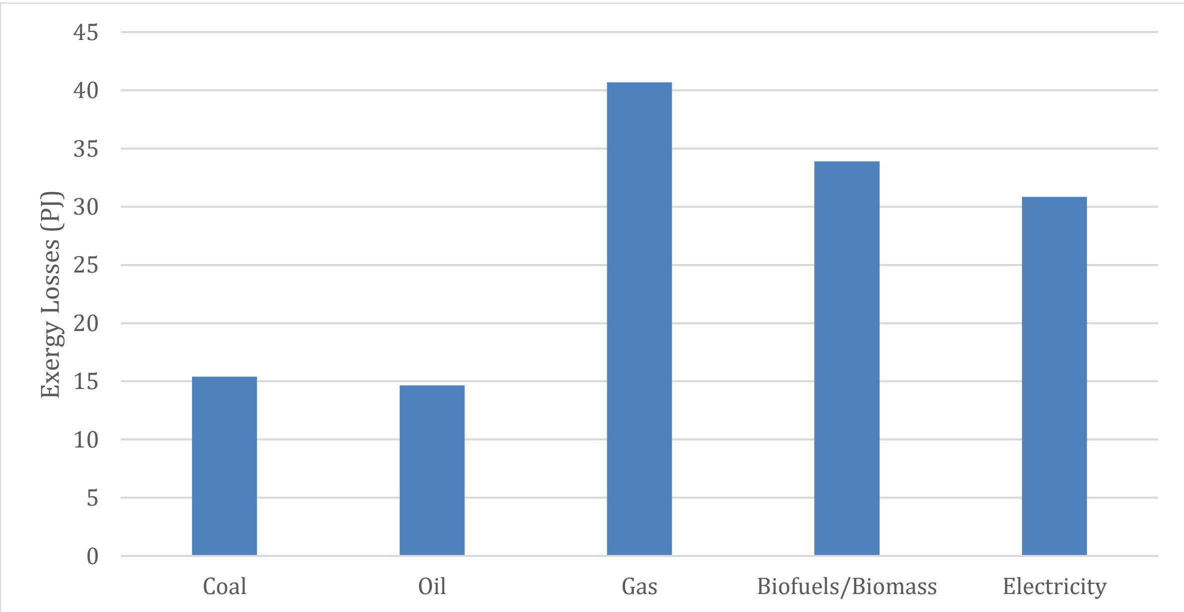


The transformation sector shows the highest energy losses (203PJ, 44% of total energy losses), and this is due to the impact of the quality of geothermal steam in energy analysis. Exergy losses from the transformation sector account for a much lower 15% (76PJ) of total exergy losses because this geothermal steam quality is accounted for in the exergy analysis. 37% of New Zealand's TPExS passes through the transformation sector, so the high losses here can be attributed to high resource flows.

The transport sector accounts for the highest proportion (34%, 158PJ) of exergy losses in New Zealand. The transport sector has low energy and exergy efficiencies, and it consumes 25% (192PJ) of New Zealand's TPES and 30% (206PJ) of New Zealand's TPExS. This means that the transport sector is responsible for the largest proportion of exergy losses, and is a key area where improvements should be focused.

The industrial sector is responsible for 13% (140.9PJ) of New Zealand's exergetic losses. There are large losses here due to the scale of consumption, despite the industrial sector being one of the most exergy efficient sectors. This effect is mirrored within the industrial sector when individual resources are examined.

Figure 35. Exergy losses in the industrial end-use sector, by resource



Some of the largest industrial exergy losses are from gas and electricity consuming processes, but these processes are overall the most efficient end-use processes within New Zealand. It is the scale of consumption here that leads to large losses. It is important to note that exergy losses can never be completely reduced to zero as there will always be losses from energy conversion processes. Large losses can indicate an efficient sector that operates on a large scale. On the other hand, biofuels and biomass are not consumed at the same scale as gas and electricity, and the large losses that can be seen in Figure 35 are due to inefficient processes.

The residential and commercial sectors have comparatively low energy and exergy losses, due to the low energy and exergy flows through the sector and that these two sectors have some of the lowest energy and exergy efficiencies.

11.3. Implications for Future Improvements to New Zealand's Energy System

The results of an exergy analysis should be considered for future development of New Zealand's energy system. When thinking about future improvements to New Zealand it is more appropriate to look at individual processes and technologies rather than overall sectors. The residential and commercial sectors are the least exergy efficient, but the key processes that cause this are low temperature space and water heating. This indicates that future development should be focused on replacing old heating technology with new technology such as efficient heat pumps.

The transport sector is energy and exergy inefficient, and responsible for a large proportion of New Zealand's energy resource use. Petrol and diesel engines do not effectively convert the energy stored in gasoline to power the wheels of the vehicle, with energy efficiencies of 13% (petrol) and 22% (diesel) and exergy efficiencies of 12% (petrol) and 21% (diesel). A key solution to this would be increasing the electric vehicle fleet within New Zealand and replacing old petrol and diesel engines with electric vehicles. Electric vehicles have an efficiency of 59% - 62% [72], and this efficiency will continue to improve as new technologies are developed. It can be expected that the exergy efficiency of these vehicles is similar to their energy efficiency, as their major output is work. In the extreme case where New Zealand had 100% electric vehicles, exergetic losses in the transport sector could fall by 88% and transport exergy demand could fall by 73%.

Table 50. Comparison between petrol and diesel engines and electric vehicles in the transport sector

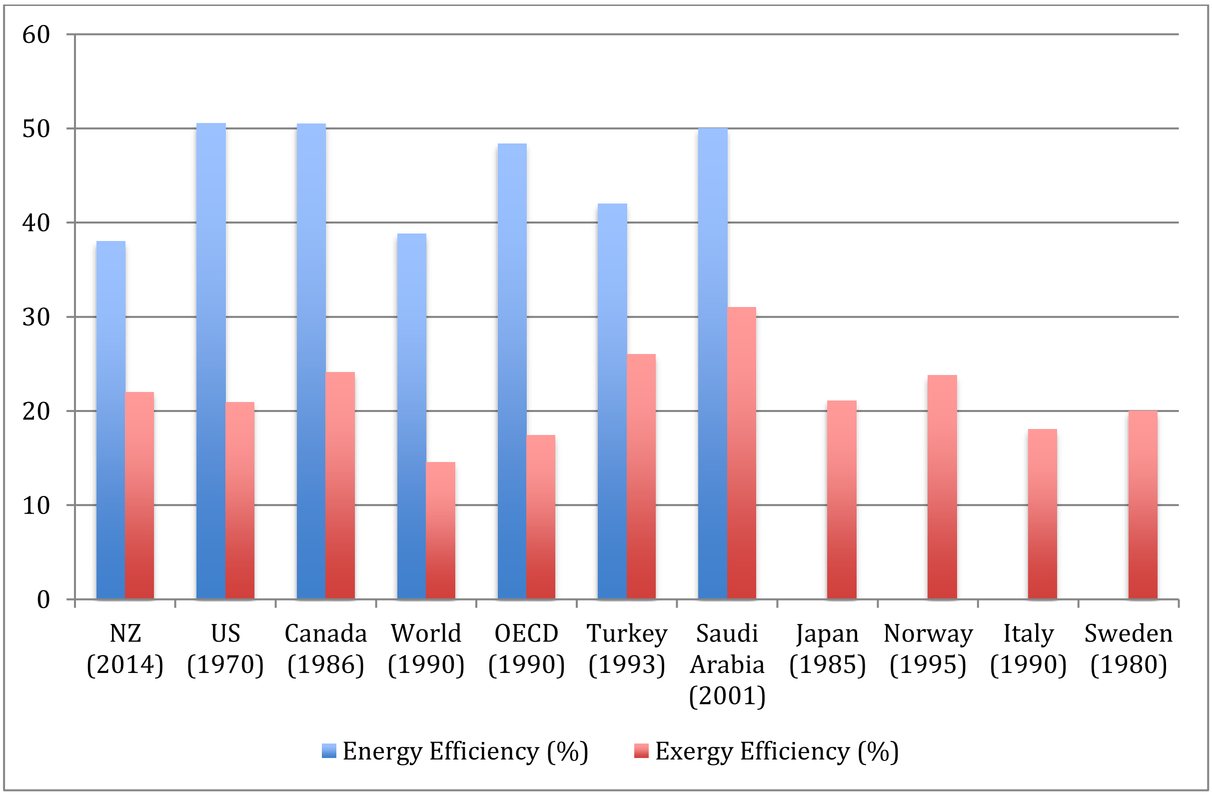
	Petrol and Diesel	Electric Vehicles	% Drop
Delivered Exergy (PJ)	205.5	55.2	73
Exergy Product (PJ)	34.2	34.2	
Exergy Losses (PJ)	171.3	21.0	88
Exergy Efficiency (%)	17	62	

The future developments suggested above both require large electricity supply, which can be provided by both reducing national demand through increased end-use efficiency, and by increasing electricity supply. An exergy analysis indicates that renewable electricity generation developments are an appropriate way to increase electricity supply. New Zealand already has a strong history of developing its renewable resources, and an exergy analysis gives additional support for these practices.

11.4. Comparison with Other Countries

In the introduction to this thesis, a number of exergy studies of other countries were introduced. The overall energy and exergy efficiencies of these analyses have been collated in Figure 36, and are compared to the results of this thesis. The countries which only show exergy efficiencies have been analysed with the exergy of food and crops being considered, so an energy analysis was not carried out in these studies. It should be noted that the analyses from which the country's data has been sourced are from different years, which means that the countries should not be directly compared, but should be used to understand general trends.

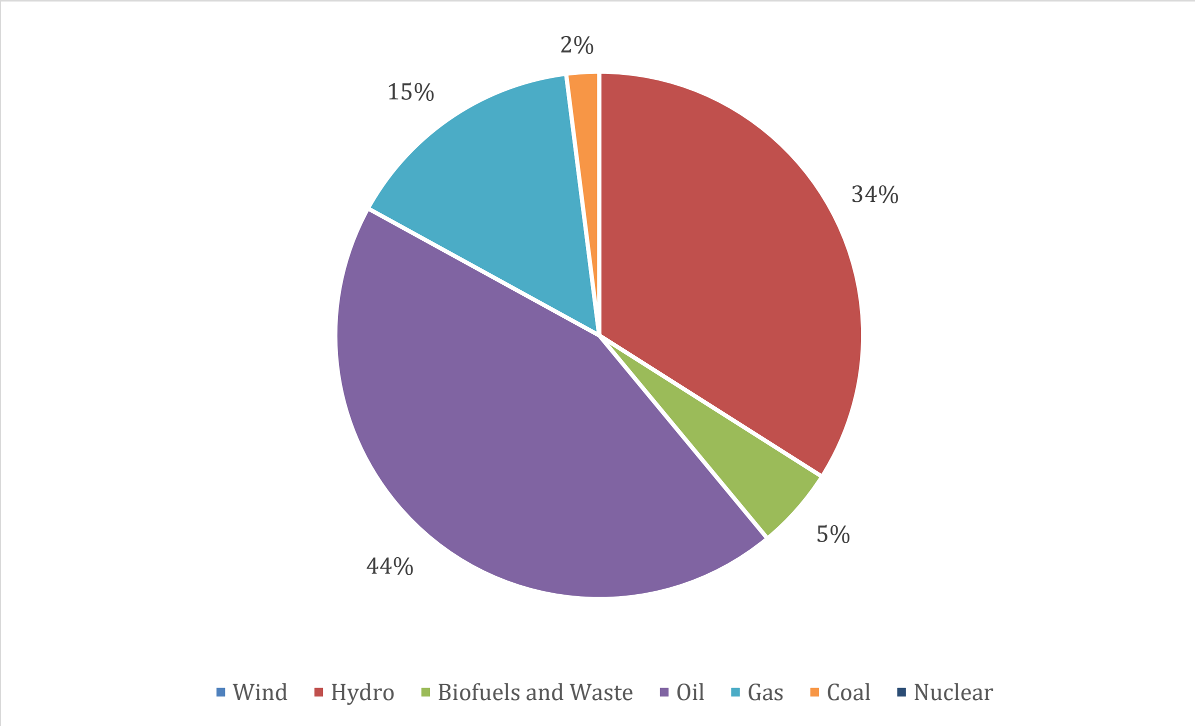
Figure 36. National energy and exergy efficiencies



First, the results from other countries act as a validation tool for the results of this thesis. The New Zealand energy and exergy efficiencies that have been calculated are similar to those found in other countries. New Zealand's energy efficiency is the lowest shown in this figure, but this is due to the large proportion of geothermal energy in New Zealand. New Zealand's exergy efficiency sits within the range of exergy efficiencies of other countries.

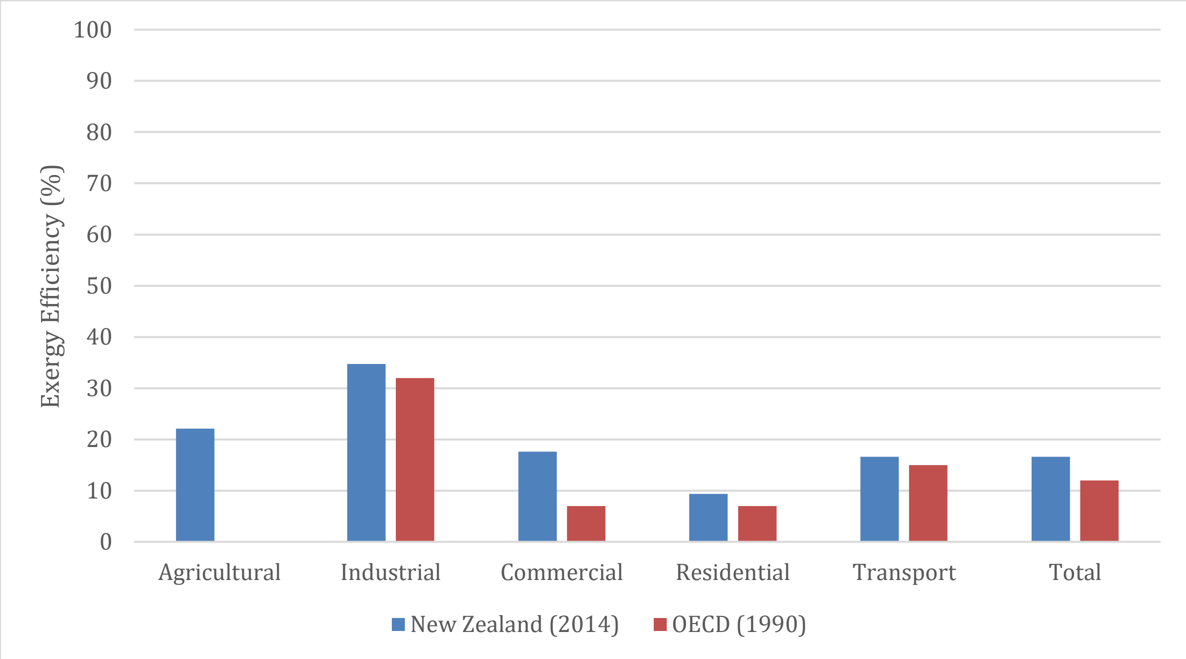
Norway has a similar economic structure and natural resource make up to New Zealand. Norway has large amounts of hydropower and oil consumption, although there is no large scale geothermal resource utilised in Norway, which can be seen in Figure 37. This can be compared to Figure 32, which shows New Zealand's TPES.

Figure 37. Total Primary Energy Supply for Norway, 2013 [73]



From Figure 36, Norway has a 24% exergy efficiency, and New Zealand has a 20% exergy efficiency. These two results should not be directly compared as the Norway study includes the exergy of food and material goods, but they give a good indication of the similarity between the countries. The most applicable comparison can be made between New Zealand and the OECD average, which does not include the exergy of food and material goods. New Zealand's energy efficiency is lower, and exergy efficiency is higher than the OECD average. These overall efficiency results are broken down to efficiencies of each sector in Figure 38.

Figure 38. Global comparisons of exergy efficiencies of end-use sectors [8]



Common trends are that the industrial sector has the highest exergy efficiency, which is due to the high quality, high temperature resources that this sector utilises. The commercial and residential sectors are combined for OECD data, so the same efficiency is used for each separate sector for comparison to New Zealand's results. New Zealand performs better than the OECD average in every sector, which may be due to the large amount of renewable energy and high electricity infiltration in New Zealand, or due to the difference in year between the studies.

11.5. Productivity

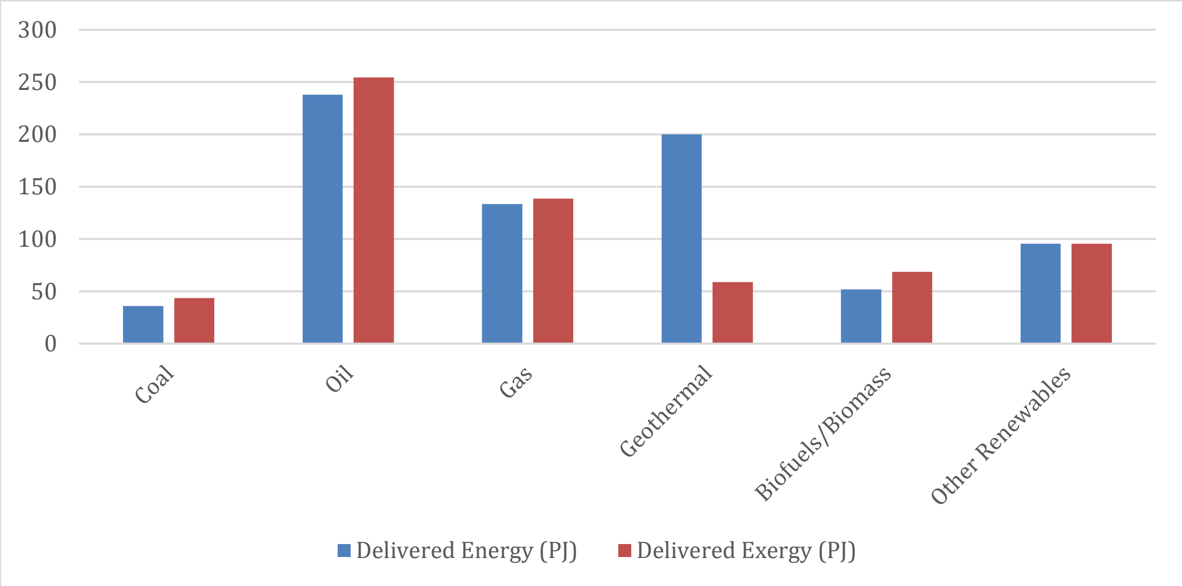
Exergy analysis offers new insights into the productivity of an economy. Energy productivity is increasingly used to describe a country's ability to derive value added from energy resources. For an economy, energy productivity is the ratio of value added to energy consumption. The research that has been presented in this thesis has shown that energy is not a suitable indicator to accurately describe the potential and efficient utilisation of a resource. Neither energy efficiency nor energy productivity effectively capture the maximum work potential of resources, and an economy's ability to capture this work potential. It is proposed that an exergy productivity analysis is a more suitable assessment of a country's productivity. Table 51 below shows the calculations of energy and exergy productivity in New Zealand.

Table 51. Energy and exergy productivity of New Zealand, 2014

Delivered Energy (PJ)	764
Delivered Exergy (PJ)	679
2014 GDP (Mill USD) [74]	170068
Energy Productivity (Mill USD/PJ)	223
Exergy Productivity (Mill USD/PJ)	251

New Zealand has a higher exergy productivity than energy productivity. This is mostly due to difference in delivered energy and exergy for geothermal fluid. The delivered energy and exergy for each energy resource used in New Zealand can be seen in Figure 39.

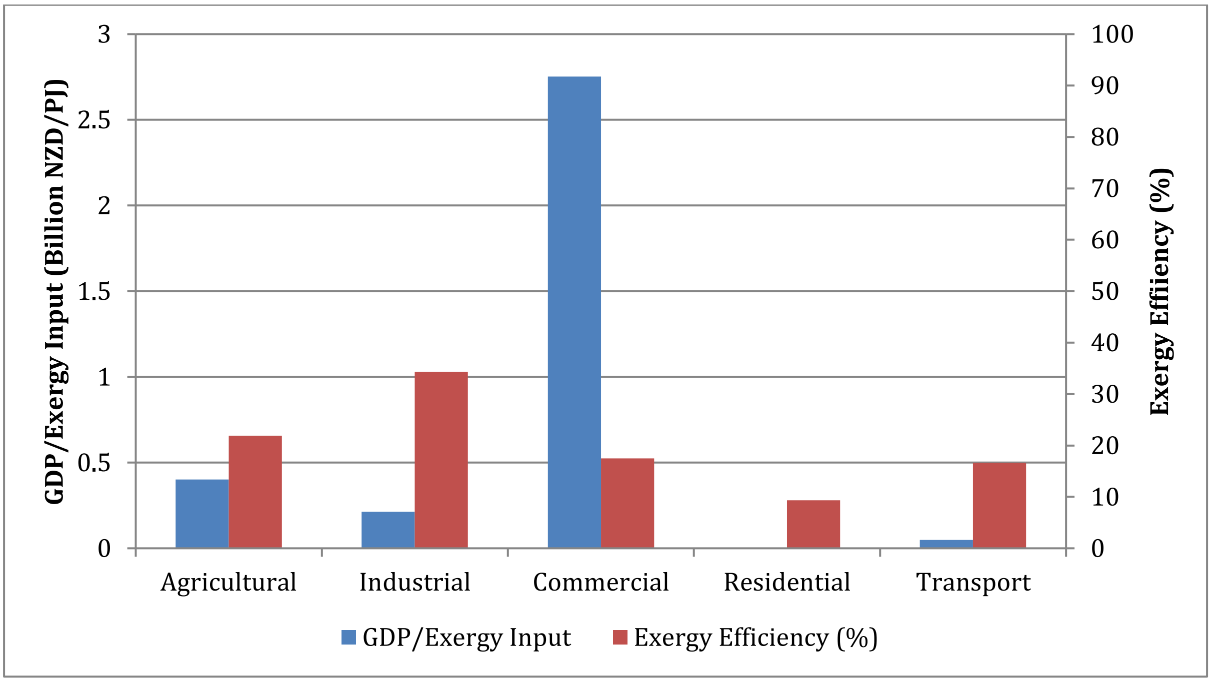
Figure 39. Delivered energy and exergy from each energy resource, 2014



While the other resources have higher delivered energy values than delivered energy, geothermal is the opposite of this. The difference between delivered energy and exergy for geothermal fluid is much larger than that for other energy resources. These two aspects mean that total delivered exergy is higher than total delivered energy, and this in turn leads to a higher exergy productivity than energy productivity.

New Zealand's exergy productivity per sector is shown below in Figure 40.

Figure 40. Exergy productivity and exergy efficiency of end-use sectors in New Zealand, 2014



An interesting observation is that, although the commercial sector has low exergy efficiency, it has the highest GDP/exergy input ratio. Data and sources for these calculations can be seen in Appendix H. This indicates that, although there is lost work potential from low efficiency processes and low quality outputs, there is an additional productivity coming from this sector that does not have an exergy value associated with it and is not captured in an exergy analysis.

In an economy that encourages to the most efficient use of its resource through market driven changes, it makes sense that high quality natural resources would be utilised in the processes that can produce maximum outputs, such as electricity generation or high temperature industrial processes. Additionally, the sectors other than commercial all act in support of the commercial sector. The agricultural and industrial sectors create products for trading in the commercial sector. The residential sector has no GPD, but the delivered exergy to this sector is also in support of all other sectors. The exergy delivered to the residential sector could be seen as the fuel of the work force that carries out the activities in the other sectors. Figure 40 indicates that there is additional value being produced by the commercial sector that justifies the low exergy efficiency of its end-use processes.

11.6. Methodological Shortcomings and Improvements to this Analysis

In this section, we point out various improvements that could be made to the current analysis. The main improvement that could be made to this analysis is having access to complete data sets. The current data systems within New Zealand are set up for energy data. As this is the first time a national exergy analysis has been carried out for New Zealand, a lot of the data that was required that were not publicly available and were difficult to access and collate. This is particularly applicable for the analysis of geothermal systems. There was little available data for steam temperature and pressure at the different inlets and outlets within geothermal power stations. Accurate data collection for the flow of all energy resources throughout New Zealand would greatly improve the quality of the exergy analysis, and would facilitate repetition and long term studies. Additionally, while the EECA End-Use Database provided energy input and product data at a very fine level, exergy analysis of fossil fuels requires mass flows. These mass flows were approximated from the energy values and NCVs.

There is potential for improvement of assumptions made for the analysis of hydropower, wind and solar PV electricity generation systems. Currently, the delivered exergy is assumed to be equal to the delivered energy. This is due to the complexities in defining the maximum potential of the delivered renewable energy resource on a national scale.

Individual studies should be carried out for hydropower, wind and solar PV to explore the exergy flows of each of these technologies. This is specifically applicable for hydropower because of the large amount of hydro-generation that occurs in New Zealand. For wind, an appropriate assessment of exergy could be according to Betz's law, which states that no turbine can capture more than 59.3% of the kinetic energy in wind [71].

There is room for improvement in the analysis of non-heat end use processes. The exergy efficiencies that were used for non-heat end-use technologies were from 1975, and there have been many improvements to the efficiency of technologies since then. Each technology should be analysed individually to determine energy and exergy efficiencies.

There were some inconsistencies within this analysis with regards to environmental temperature following the method set out by Reistad [3]. The environmental temperature is set to 25°C when calculating the exergy of fuels using the equations in Table 4, but this cannot be the temperature for space heating processes as space heating mostly does not occur when the environment is this warm. The environmental temperature is modified when calculating the exergy of end-use products. This led to some differences between environmental temperatures of input and output exergies. In order to resolve this, separate input exergies of fuels could be calculated for each end-use process according to the specific environmental temperature.

11.7. Future Work

There are many areas where an exergy analysis could be implemented to improve understanding of New Zealand's energy systems, a key area being the annual MBIE energy analysis. An exergy analysis, like the one carried out in this thesis, could easily be included within the MBIE data tables. Much of the data already comes from these data tables, and the exergy analysis has more impact when it can be compared to a similar energy analysis. This analysis could be carried out each year to start building up a database of annual exergy flows through New Zealand. The New Zealand exergy analysis could also be extended into historic data to understand how New Zealand's management and consumption of its energy resources has changed in the past.

Following on from section 11.6, the concept of exergy productivity could be extended to analysis of the entire country. This assessment should look at long term trends of a country rather than comparing other countries, as the economic structure of the country would have more influence on the GDP/exergy input ratio. A trend of exergy productivity over time could be calculated for New Zealand. These trends give a clearer understanding of exergy productivity in New Zealand. MBIE already provide historic data for production of energy resource production and transformation. Historic end-use data is not readily available, and it is for this reason that a historic analysis was not included in the current analysis. For a separate project, additional research could be carried out to calculate or approximate this historical end-use consumption. With this data, a total historic exergy analysis could be carried out. The historic data could also have some implications for future development. The analysis could show the impact that changes that happened in the past had on the way the energy system operated, and this would give further insight into how changes now might impact the future of New Zealand. A historical exergy analysis might also give more information on whether the market naturally tends towards high exergy efficiency, as there may be an inherent understanding of the maximum potential of fuels that drives development in this way. In a similar manner, it may also be interesting to analyse the future planned changes to New Zealand's energy system from an exergy perspective.

Another aspect of exergy research that could be carried out is exploring changes in technology, and which technological shifts give the most gain in exergy efficiency. This is especially applicable for transport, and it has been suggested previously in this thesis that a change to a transport sector dominated by electric vehicles would provide massive improvements in exergy use. Analysis like this could be carried out for each end-use process to determine the most suitable technology for creating each end-use product. An example of this the comparison between the fuels and technologies used in the commercial sector for space heating, presented in Table 52.

Table 52. End-use resource comparison for low temperature commercial space heating

Fuel and technology	Energy Efficiency (%)	Exergy Efficiency (%)
Coal – Boiler systems	75	1.4
Oil – Boiler systems	85	1.6
Natural Gas - Boiler systems	85	2
Electricity – Heat pump	COP 3.8	72
Electricity – Resistance heater	100	1.2

Electric heat pumps are a much more suitable space heating option than all other options as the exergy efficiency is much higher.

A similar idea to technological shifts is that of resource allocation. Resource allocation would look at the amount of resources available in New Zealand, and seek to optimise their consumption by reducing exergy losses by shifting resources to processes where they are more efficient. An example of this is coal use in New Zealand. Electricity generation from coal at the Huntly power station is an inefficient utilisation of this resource, with an energy efficiency of 46% and exergy efficiency of 39%. High temperature industrial processes that use coal have energy and exergy efficiencies of 70% and 43% respectively. These industrial processes are a more suitable use for the coal that is currently being consumed at Huntly.

12. Conclusions

An exergy analysis has been carried out on the New Zealand energy system. The energy and exergy flows for each energy resource utilised in New Zealand were individually analysed. These energy resources are coal, oil, natural gas, geothermal, biofuels, and other renewable energy resources. The energy resources are utilised in different processes, which were divided into transformation processes and end-use processes. Transformation processes included electricity generation and cogeneration. End-use processes included a wide range of processes within the agricultural, industrial, commercial, residential and transport sectors. These end-use processes included, but were not limited to; high, medium and low temperature process requirements, space and water heating, and mobile and stationary motive power. Each end-use process was assessed per the technology used, such as furnace/kiln and boiler systems, cooking ovens, and internal combustion engines. Energy and exergy values were calculated at each stage as primary energy resources are transformed to final consumer energy products and then to energy services in end-use technologies.

From these energy and exergy flows, efficiencies were also calculated for each transformation and end use process for each resource type. New Zealand had an overall energy efficiency of 38% and an overall exergy efficiency of 22%. Efficiencies for sub-systems of the energy sector were also calculated. Generally, exergy efficiencies were lower than energy efficiencies. This was not the case for geothermal electricity generation systems. This exergy analysis revealed that the geothermal resource utilised in New Zealand was much smaller than an energy analysis would conclude. This has a large impact on the overall perspective of New Zealand's energy system because 16% of electricity generation is from geothermal resources. 26% (200PJ) of New Zealand's primary energy is geothermal energy, while only 9% (59PJ) of New Zealand's primary exergy is geothermal exergy. Geothermal is responsible for a much smaller proportion of primary resource than what energy analysis concludes, and this in turn changes the overall view of the diversification of New Zealand's delivered energy.

There is potential for this work to be continued for further insight into the impact that exergy analysis can have on the development of a country. While the exergy analyses of other countries can be compared to the results of this thesis, there are many other factors that can make a direct comparison difficult. Exergy analysis can be carried out on historic data sets to find trends in development, and these can be projected forward to offer insight into future developments.

The greatest improvement to this exergy analysis would be more accurate data. There were areas where available data was lacking, so approximations and assumptions were made. This is specifically applicable for geothermal data, which was obtained from many different sources, and not from a single cohesive database.

The exergy analysis of New Zealand offers new insights into how the country's energy resources are utilised. The conclusions from this study differ from those from energy analyses, and indicate that current analysis methods do not accurately describe the utilisation of energy resources in New Zealand's energy system.

Appendix A: General

Appendix A.1: Energy Resources and Users in New Zealand

Table 53. Coal major producers and users [17]

Coal	
Major Producers	**Location**
Huntly Coalfield	Waikato
Rotowaro Coalfield	Waikato
Buller Coalfield	West Coast
Greymouth Coalfield	West Coast
Ohai Coalfield	Southland
Southland Lignites	Southland
Imports	Indonesia and Australia
Major Users	**Location**
Huntly Power Station	Waikato
NZ Steel Mill	Auckland
Golden Bay Cement	Whangarei
Exports	To India, Japan, China, South Africa
Domestic consumption	Nationwide

Table 54. Oil major producers and users [17]

Oil	
Fields	**Location**
Kupe	Taranaki
Maari	Taranaki
Tui	Taranaki
Pohokura	Taranaki
Maui	Taranaki
McKee/ Mangahewa	Taranaki
Ngatoro	Taranaki
Turangi	Taranaki
Kowhai	Taranaki
Rimu	Taranaki
Kapuni	Taranaki
Imports	The Middle East, Singapore, South Korea, Russia, Nigeria, Australia
Major Users	**Location**
Marsden Point	Northland
Exports	Australia
Transport	Nationwide

Table 55. Natural gas major producers and users [17]

Natural Gas	
Fields	**Location**
McKee	Taranaki
Mangahewa	Taranaki
Maui	Taranaki
Kupe	Taranaki
Kapuni	Taranaki
Ngatoro	Taranaki
Kowhai	Taranaki
Turangi	Taranaki
Pohokura	Taranaki
Rimu/ Kauri	Taranaki
Cheal	Taranaki
Sidewinder	Taranaki
Major Users	**Location**
Methanex	Taranaki
Electricity Generation Sites	**Location**
Auckland District Hospital	Auckland
Bay Milk Edgecumbe	Bay of Plenty
Kapuni	Taranaki
Kawerau - TPP	Bay of Plenty
Kiwi Dairy, Hawera (Whareroa)	Taranaki

Te Awamutu - Anchor Products	Waikato
Te Rapa	Waikato
Wellington Hospital	Wellington
Forest Research	Bay of Plenty
Huntly e3p	Waikato
Huntly p40	Waikato
Mangahewa	Taranaki
New Plymouth	Taranaki
Otahuhu A	Auckland
Otahuhu B	Auckland
Southdown	Auckland
Stratford Peaker	Taranaki
Taranaki Combined Cycle	Taranaki

Table 56. Geothermal major producers and users [17]

Geothermal	
Power Plants	**Location**
Kawerau Power Plant	Bay of Plenty
KA24	Bay of Plenty
Kawerau Binary, TG01 and TG02	Bay of Plenty
Mokai Power Plant (1, 2, 1A)	Waikato
Ngatamariki Power Station	Waikato
Ngawha Power Station	Northland
Ohaaki Power Station	Waikato
Rotokawa Power Station	Waikato
Nga Awa Purua Power Station	Waikato
Te Huka Power Station	Waikato
Wairakei Binary Power Station	Waikato
Poihipi Road Power Station	Waikato
Te Mihi Power Station	Waikato
Secondary Use	**Location**
Norske Skog Tasman Pulp and Paper Mill	Bay of Plenty
Carter Holt Harvey Tasman Wood production	Bay of Plenty
SCA Hygiene Australia	Bay of Plenty
Mokai Glass House	Waikato
Miraka Whole Milk Powder Plant	Waikato
Ohaaki Thermal Kilns	Waikato

Tenon Kilns	Waikato
Wairakei Prawn Farm	Waikato
NETCOR Tourism Facility	Waikato
Wairakei Resort Hotel	Waikato

Table 57. Biogas major producers and users [17]

Biogas	
Landfills	**Location**
Greenmount	Auckland
Rosedale	Auckland
Redvale	Auckland
Whitford	Auckand
Hamilton	Hamilton
Palmerston North	Palmerston North
Tirohia (Hauraki)	Tirohia
Nelson	Nelson
Hampton Downs	Waikato
Happy Valley	Wellington
Silverstream	Lower Hutt
Spicer Landfill	Porirua/ Wellington
Burwood Landfill	Christchurch
Waste Water Treatment Plants	**Location**
Tauranga WWTP	Tauranga
Christchurch Bromley WWTP	Christchurch
Mangare WWTP	Auckland
Northshore	Auckland
Hamilton WWTP	Hamilton
Piggery Waste	Waikato

Tirau Dairy	Tirau
PNCC digester upgrade	Palmerston North
Green Island digester	Dunedin
Hamilton CC digester upgrade	Hamilton
Industrial Digester	**Location**
Piggery Waste	Canterbury
Beef feedlot manure	Canterbury
Piggery feedlot manure	Waikato
Kiwifruit waste	Tauranga
Chicken waste	Waikato
Piggery waste	Canterbury

Table 58. Woody biomass major users [17]

Woody Biomass	
Major Users	**Location**
Kawerau - CHH	Bay Of Plenty
Kinleith	Waikato
Pan Pac	Hawkes Bay
Fletcher Forests	Bay Of Plenty

Table 59. Hydro major generating sites (December 2011, 10MW or greater) [19], [40]

Hydro	
Power Plants	**Location**
Aniwhenua	Bay of Plenty
Arapuni	Waikato
Aratiatia	Waikato
Argyle - Branch	Nelson/Marlbourough
Atiamuri	Waikato
Aviemore	South Canterbury
Benmore	South Canterbury
Clyde	Otago/Southland
Cobb	Nelson/Marlbourough
Coleridge	Canterbury
Highbank	Canterbury
Kaimai	Bay of Plenty

Kaitawa	Hawkes Bay
Karapiro	Waikato
Kumara	West Coast
Manapouri	Otago/Southland
Mangahao	Central North Island
Maraetai	Waikato
Matahina	Bay of Plenty
Ohakuri	Waikato
Ohau A	South Canterbury
Ohau B	South Canterbury
Ohau C	South Canterbury
Patea	Taranaki
Patearoa/Paerau	Otago
Piripaua	Hawkes Bay
Rangipo	Central North Island
Roxburgh	Otago/Southland
Tekapo A	South Canterbury
Tekapo B	South Canterbury
Teviot	Otago/Southland
Tokaanu	Central North Island
Tuai	Hawkes Bay
Waipapa	Waikato
Waipori	Otago/Southland

Waitaki	Otago/Southland
Whakamaru	Waikato
Wheao	Bay of Plenty

Table 60. Wind major generating sites [17]

Wind	
Generating Sites	**Location**
Brooklyn	Wellington
Gebbies Pass	Canterbury
Hau Nui (Stage 1)	Wairarapa
Hau Nui (Stage 2)	Wairarapa
Southbridge	Canterbury
Tararua (Stage 1)	Manawatu
Tararua (Stage 2)	Manawatu
Tararua (Stage 3)	Manawatu
Te Apiti	Manawatu
Te Rere Hau	Manawatu
White Hill	Southland
West Wind	Wellington
Horseshoe Bend	Central Otago
Weld Cone	Marlborough
Chatham Islands	Chatham Islands
Lulworth	Marlborough

Te Uku	Waikato
Mahinerangi	Clutha
Mt Stuart	Clutha
Mill Creek	Wellington
Lake Grassmere	Marlborough
Flat Hill	Bluff

Appendix A.2: ANZSIC 2006 Code Classifications of End Uses

Table 61. End-use classifications by sector [26]

End Use	Sector
Accommodation and Food Services	Commercial and public services
Arts, Recreational and Other Services	Commercial and public services
Building Cleaning, Pest Control and Other Support Services	Commercial and public services
Central Government Administration	Commercial and public services
Construction	Industry
Dairy Cattle Farming	Agriculture/forestry and Fishing
Dairy Product Manufacturing	Industry
Defence	Commercial and public services
Education and Training: Pre-School, Primary and Secondary	Commercial and public services
Education and Training: Tertiary Education and Other Education	Commercial and public services
Electricity, Gas, Water and Waste Services	Industry
Financing, Insurance, Real Estate and Business Services	Commercial and public services
Fishing, Hunting and Trapping	Agriculture/forestry and Fishing
Forestry and Logging	Agriculture/forestry and Fishing
Furniture and Other Manufacturing	Industry

Health Care and Social Assistance	Commercial and public services
Household	Residential
Household (Private Transport)	Residential
Indoor Cropping	Agriculture/forestry and Fishing
Information Media and Telecommunications	Commercial and public services
Local Government Administration	Commercial and public services
Meat and Meat Product Manufacturing and Seafood	Industry
Mining	Industry
Non-Dairy Agriculture	Agriculture/forestry and Fishing
Non-Metallic Mineral Product Manufacturing	Industry
Other Food Product Manufacturing	Industry
Petroleum, Basic Chemical and Rubber Product Manufacturing	Industry
Primary Metal and Metal Product Manufacturing	Industry
Printing	Industry
Public Administration and Safety	Commercial and public services
Pulp, Paper and Converted Paper Product Manufacturing	Industry
Retail Trade - Food	Commercial and public services
Textile, Leather, Clothing and Footwear Manufacturing	Industry
Transport Equipment, Machinery and Equipment Manufacturing	Industry
Transport, Postal and Warehousing	Transport
Transport, Postal and Warehousing (Commercial-Non-Transport)	Commercial and public services

Wholesale and Retail Trade - Non Food	Commercial and public services
Wholesale Trade - Food	Commercial and public services
Wood Product Manufacturing	Industry

Appendix A.3: Definitions of Sector and Process Classifications

Table 62. Definitions of sector and process classifications

Category	Definition
Available supply	
Indigenous production	Resources produced within New Zealand.
Imports	Resources imported into New Zealand from other countries.
Exports	Resources exported to other countries from New Zealand.
Stock change	"Change in the level of stocks between ends of months, quarters or years. By convention, an increase in stock levels is defined as a positive stock change." [19]
Non-energy use	"Use of fuels for non-combustion purposes (e.g. bitumen for roads and natural gas used as feedstock for the production of methanol and ammonia/urea)." [19]
Transformation processes	"The conversion of energy from one form to another" [19]
Electricity generation	Electricity generation from coal, oil, natural gas, geothermal, hydro, wind, solar, biofuels and waste heat. Not including combined heat and power plants [19]
Cogeneration	"The simultaneous or sequential production of two or more forms of useful energy from a single primary energy source. In this publication, a

	cogenerator is an electricity-generating facility that produces electricity and a form of useful thermal energy (such as heat or steam for industrial or commercial heating or cooling purposes)" [19]
Other coal transformation	This is the coal that is used as a carbon source for steel production, and is not used for its energy content.
Oil production	"Including refinery operations and the manufacture of synthetic fuel from natural gas" [17]
End use sectors	
Agricultural	"This sector includes all types of farming, hunting, forestry, logging, fishing and aquaculture. For gas and electricity, it excludes separately metered farm houses, which are included in the residential sector, but includes houses where separate metering is not available and farming activity is the dominant use." [19]
Industrial	"An energy-consuming sector that consists of all facilities and equipment used for producing, processing or assembling goods. The industrial sector encompasses activities such as manufacturing, metal production, and construction. Overall energy use in this sector is largely for process heat and cooling and powering machinery, with

	lesser amounts used for facility heating, air conditioning and lighting." [19]
Commercial and public services	"This sector includes non-manufacturing business establishments such as hotels, motels, restaurants, wholesale businesses, retail stores, and health, social and educational institutions. It also includes electricity used in public lighting, railway and urban traction." [19]
Residential	"An energy-consuming sector that consists of living quarters for private households. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a variety of other appliances." [19]
Transport	Includes international and domestic transport by air, land, rail and sea.
End use processes	"These are useful energy outputs which result from end-use processes in a given economy. They include those proportions of energy actually useful to consumers" [47]
High temperature heat (>300C) process requirements	"This refers to those end-uses of heat in industrial processes where heat is required at temperatures of greater than or equal to 300ºC. This includes the heat requirements of processes in the iron and steel, cement, engineering and kilning industries, where

	heat temperatures exceeding 1000ºC are often required.” [47]
Intermediate heat (100-300C) process requirements	“This refers to those end-uses of heat in industrial processes where heat is required at temperatures between 100-300ºC. This includes most of the heat used in the chemical, paper, food and textile industries. This is split into 3 sub-categories: ‘kiln and furnace’, ‘industrial ovens’ and ‘general’ (which mainly includes boiler applications).” [47]
Low temperature heat (<100C) process requirements	“This refers to end-uses of where heat is required at temperatures below 100ºC. This occurs mainly in the wood and food processing industries. This is split into 2 subcategories: ‘kiln/furnace’ and ‘general’ (which mainly includes boiler applications).” [47]
Aluminium manufacturing	“This refers to the electro-chemical reduction of aluminium oxides (primarily $A1_2O_3$) to elemental aluminium.” [47]
Electronics and other electrical uses	“This refers to electrical energy used by electronic equipment such as televisions, radios and computers. The systems boundary is drawn at the end-use efficiency of such equipment.” [47]
Iron and steel manufacturing	“This refers to the chemical reduction of Fe_3O_4 to elemental iron.” [47]
Lighting	“This refers to lighting of streets, road and other vehicular routes for safety and security reasons. This mainly includes

	fluorescent, high intensity discharge and high pressure sodium lights". [47]
Low temperature heat (<100C) clothes drying	"This refers to the removal of water from clothes that have been washed." [47]
Intermediate heat (100-300C) Cooking	"This refers to the heating of cooking loads in households, restaurants, cafes and other similar situations. It only includes heat actually entering the cooking load." [47]
Low temperature heat (<100C) space heating	"This refers to the heating of rooms primarily in the household and commercial sectors to an acceptable environmental temperature of about 20º-25ºC." [47]
Low temperature heat (<100C) water heating	"This refers to the heating of water in the household and commercial sectors to relatively low temperatures (50°C-70°C)." [47]
Motive power, mobile	"This is mechanical power generated by a mobile machine (forklift, tractor, grader) in an off-road situation. It does not include the use of cars, trucks, vans or other vehicles that are primarily used on road, even if they are being used in an 'off-road' situation." [47]
Motive power, stationary	"This is mechanical energy generated mainly in industrial situations from stationary engines and motors." [47]
Pumping	"This refers to energy being applied to move a fluid along a system of pipes and valves. The systems boundary is drawn at

	the point of the fluid entering the pumping system under pressure, and where losses due to the electric motors operating the system are taken into account. This does not include losses in the pumping system itself; such as head losses, friction losses, and losses due to value and joint enlargement which are all extremely difficult to quantify." [47]
Refrigeration	"This refers to the removal of heat from refrigeration spaces (cabinets, rooms, stores) so as to attain a temperature below 3ºC." [47]
Space cooling	"This refers to the cooling of rooms primarily in the household and commercial sectors to an acceptable environmental temperature of about 20º-25ºC." [47]
Transport, air	"This refers to that mechanical energy required to power aircraft, taking full account of friction and other losses. This includes both domestic aircraft, as well as aircraft travelling overseas but receiving fuel in New Zealand." [47]
Transport, land	"This refers to that mechanical energy required to power road and land vehicles taking full account of friction and other losses. These vehicles include automobiles, trucks, buses, motor cycles, tractors and other related vehicle types which operate on roads and/or land

	surfaces. Land transport is split into *3 sub-categories* in the OPENZ optimisation matrix: Freight, Passenger Cars, Passenger Buses." [47]
Transport, rail	"This refers to that mechanical energy required to power railroad stock, taking full account of friction and other losses." [47]
Transport, sea	"This refers to that mechanical energy required to power vessels that are designed to move across the surface of water bodies, taking full account of friction and other losses." [47]

Appendix A.4: Information on Generating Plants

Table 63. Information on Generating Plants December 2014 [15]

Plant type	Plant Name	Owners/Operators	Commissioned	Capacity (MW)
Biomass/Coal/Gas	Kawerau A&B (Wood)	Carter Holt Harvey - Tasman	1966	19
Biomass/Coal/Gas	Kinleith Cogen	CHH&Genesis	1998	40
Biomass/Coal/Gas	PanPac Steam Cogen	Pan Pac	2005	13
Coal/Gas	Huntly Units 1-U41	Genesis Energy	1987	500
Coal/Gas Waste	Glenbrook Cogen	NZ Steel	1987/1997	112
Diesel	Whirinaki[1]	Contact Energy	2004	155
Gas	Edgecumbe Cogen	Bay of Plenty (Todd Energy)	1996	10
Gas	Huntly Units 5~e3p CCGT	Genesis Energy	2007	385
Gas	Kapuni Cogen CCGT	Vector/Bay of Plenty (Todd Enegy)	1998	22
Gas	Southdown Cogen CCGT	Mighty River Power	1997/2007	170
Gas	Stratford Peaker	Contact Energy	2010	200
Gas	Taranaki CCGT	Contact Energy	1998/2005	370
Gas	Te Rapa Cogen	Contact Energy	2000	48
Gas	Whareroa Cogen CCGT	Fonterra Todd JV	1997	68

Gas	McKee Power Plant	Todd Energy	2013	100
Gas/Diesel	Huntly Units 6-P40 OCGT	Genesis Energy	2004	51
Geothermal	Kawerau	Mighty River Power	2008	93
Geothermal	Mokai	Tuaropaki Power	2000/2005/2007	112
Geothermal	Nga Awa Purua	Mighty River Power	2010	138
Geothermal	Ngawha	Tai Tokerau Trust/Top Energy	1998/2008	28
Geothermal	Ohaaki[2]	Contact Energy	1989	57
Geothermal	Poihipi	Contact Energy	1997/2008	50
Geothermal	Rotokawa	Mighty River Power	1997	35
Geothermal	Ngatamariki	Mighty River Power	2013	82
Geothermal	Tauhara	Contact Energy	2010	24
Geothermal	Wairakei	Contact Energy	1958/2005	132
Geothermal	Te Mihi	Contact Energy	2014	166
Hydro	Aniwhenua	Bay of Plenty (Todd Energy)	1981	25
Hydro	Arapuni	Mighty River Power	1946	178
Hydro	Aratiatia	Mighty River Power	1964	78
Hydro	Argyle - Branch	TrustPower	1983	11
Hydro	Atiamuri	Mighty River Power	1962	74
Hydro	Aviemore	Meridian Energy	1968	220

Hydro	Benmore	Meridian Energy	1966	540
Hydro	Clyde	Contact Energy	1992	400
Hydro	Cobb	TrustPower	1956	32
Hydro	Coleridge	TrustPower	1914	47
Hydro	Highbank	TrustPower	1945	25
Hydro	Kaimai	TrustPower	1972-1981	42
Hydro	Kaitawa	Genesis Energy	1947	37
Hydro	Karapiro	Mighty River Power	1948	96
Hydro	Kumara	TrustPower	1928	11
Hydro	Manapouri[3]	Meridian Energy	1971/2002/2008	730
Hydro	Mangahao	Mangahao JV	1925	38
Hydro	Maraetai	Mighty River Power	1954/1971	352
Hydro	Matahina	TrustPower	1967	76
Hydro	Ohakuri	Mighty River Power	1962	106
Hydro	Ohau A	Meridian Energy	1979	264
Hydro	Ohau B	Meridian Energy	1980	212
Hydro	Ohau C	Meridian Energy	1985	212
Hydro	Patea	TrustPower	1984	31
Hydro	Patearoa/Paerau	TrustPower	1984	12
Hydro	Piripaua	Genesis Energy	1942	44
Hydro	Rangipo	Genesis Energy	1983	120
Hydro	Roxburgh	Contact Energy	1956	280
Hydro	Tekapo A	Genesis Energy	1951	25
Hydro	Tekapo B	Genesis Energy	1977	160
Hydro	Teviot 1-7	Pioneer Generation	1983	11
Hydro	Tokaanu	Genesis Energy	1973	240
Hydro	Tuai	Genesis Energy	1929	60

Hydro	Waipapa	Mighty River Power	1961	54
Hydro	Waipori	TrustPower	1903/1955	84
Hydro	Waitaki	Meridian Energy	1936	105
Hydro	Whakamaru	Mighty River Power	1956	100
Hydro	Wheao	TrustPower	1984	26
Wind	Mahinerangi Wind Farm	TrustPower	2011	36
Wind	Tararua Wind Farm	TrustPower	1999-2007	161
Wind	Te Apiti Windfarm	Meridian Energy	2004	91
Wind	Te Rere Hau	NZ Windfarms	2006/2009/2011	49
Wind	Mill Creek	Meridian Energy	2014	60
Wind	Te Uku	Meridian Energy	2010	64
Wind	West Wind Makara	Meridian Energy	2009	143
Wind	White Hill	Meridian Energy	2007	58

Appendix A.5: National Environmental Temperature Data

Table 64. National environmental temperature data 2014 [38]

Month	Temperature (°C)
January	17.2
February	17.2
March	15.5
April	12.9
May	10.4
June	8.1
July	7.3
August	8.3
September	10.3
October	11.9
November	13.7
December	15.7
Average Year	12.4
Average Cooling Temperature (>17.3C)	18.4
Average Heating Temperature (<17.3C)	12.0

Appendix B: Coal

Appendix B.1: Coal Composition Data

Table 65. New Zealand coal data [30]

Coal Field	Strongman	Reddale	Newvale	Ohai	Rotowaro
Carbon (%)	82.62	76.89	67.83	77.11	75.07
Hydrogen (%)	5.77	5.30	4.93	5.34	5.23
Oxygen (%)	9.69	15.60	25.56	15.85	18.23
Nitrogen (%)	1.64	1.11	0.88	1.37	1.13
Sulphur (%)	0.28	1.10	0.80	0.33	0.34
Coal rank	Bituminous	Bituminous	Lignite	Lignite	Sub-bituminous
Location	West Coast	West Coast	Southland	Southland	North Island

Table 66. Huntly coalfield chemical composition data, modified to exclude ash component [75]

Hole	Can	Seam	Carbon %	Hydrogen %	Nitrogen %	Sulphur %	Oxygen %
Jasper 1	J1	Renown	74.13	5.34	1.09	0.30	19.14
Jasper 1	J2	Renown	72.99	4.97	1.26	0.27	20.52
Jasper 1	J3	Renown	73.99	5.22	1.20	0.25	19.34
Jasper 1	J4	Renown	75.36	5.13	1.22	0.24	18.05
Jasper 1	J5	Renown	75.15	5.17	1.22	0.22	18.24
Jasper 1	J6	Renown	75.85	5.23	1.23	0.20	17.50
Jasper 1	J7	Renown	75.19	5.22	1.17	0.20	18.23
Jasper 1	J8	Renown	75.00	5.07	1.21	0.20	18.53
Jasper 1	J9	Renown	75.26	5.15	1.18	0.21	18.20
Jasper 1	J10	Renown	75.25	4.98	1.28	0.24	18.26
Jasper 1	J11	Renown	73.74	5.04	1.09	0.27	19.87
Jasper 1	J12	Renown	67.15	7.35	0.80	0.35	24.35

Jasper 1	J13	Renown	72.17	7.04	0.82	0.43	19.54
Mimi 1	M1	Renown	74.57	5.27	1.18	0.27	18.71
Mimi 1	M2	Renown	75.04	5.38	1.18	0.26	18.14
Mimi 1	M3	Renown	74.58	5.19	1.21	0.24	18.79
Mimi 1	M4	Renown	74.28	5.13	1.19	0.24	19.17
Mimi 1	M5	Renown	74.00	5.18	1.19	0.21	19.41
Mimi 1	M6	Renown	74.69	5.24	1.19	0.21	18.68
Mimi 1	M7	Renown	74.40	5.12	1.18	0.22	19.09
Mimi 1	M8	Renown	74.13	5.05	1.20	0.22	19.40
Mimi 1	M9	Renown	74.77	5.10	1.19	0.23	18.71
Mimi 1	M10	Renown	74.54	5.02	1.21	0.26	18.97
Mimi 1	M11	Renown	74.45	5.43	1.11	0.35	18.66
Mimi 1	M12	Renown	72.39	6.93	0.83	0.43	19.42
Mimi 1	M2r	Renown	74.33	5.04	1.40	0.26	18.97
Mimi 1	M4r	Renown	73.71	4.89	1.43	0.24	19.73
Mimi 1	M6r	Renown	74.69	4.80	1.34	0.21	18.96
Ruawaro 2	B16	Kupakupa	74.36	5.04	1.30	0.25	19.06
Ruawaro 2	B17	Kupakupa	75.84	5.31	1.05	0.26	17.55
Ruawaro 2	B18	Kupakupa	74.74	4.91	1.29	0.23	18.83
Ruawaro 2	B19	Kupakupa	73.78	4.72	1.20	0.19	20.10

Ruawaro 2	B20	Kupakupa	76.55	5.48	0.96	0.26	16.76
Ruawaro 2	B21	Kupakupa	73.98	4.72	1.33	0.20	19.77
Ruawaro 2	B22	Kupakupa	75.18	5.21	1.28	0.23	18.10
Ruawaro 2	B23	Kupakupa	75.28	5.46	1.24	0.22	17.79
Ruawaro 2	B24	Kupakupa	75.77	5.21	1.06	0.25	17.71
Ruawaro 2	B25	Kupakupa	74.74	5.21	1.15	0.21	18.68
Ruawaro 2	B26	Kupakupa	74.19	5.30	1.20	0.36	18.95

Appendix C: Oil

Appendix C.1: Oil Calculations

Table 67. Oil and oil products carbon content [15]

Year	2013
C content (% mass)	
Premium Petrol	85.5
Regular Petrol	85.3
Jet/Kero	86.2
Auto Diesel	
Automotive Gas Oil - 50ppm	
Automotive Gas Oil - 10ppm	86.7
Marine Diesel	
Light Fuel Oil	86.7
Heavy Fuel Oil	86.2
Bunker Fuel Oil	86.0
Bitumen	86.7
Exported Naphtha	83.2

Appendix D: Natural Gas

Appendix D.1: Natural Gas Electricity Generation and Cogeneration Stations

Table 68. Natural Gas Electricity Generating Stations [40]

Station Name	Typical Annual GWh	Notes
Forest Research	0	GWh and MW data from Centralised Dataset 2006 calendar year
Huntly e3p	2410	Annual output of 2410 GWh has been estimated based on same utilisation as Otahuhu B
Huntly p40	335	Annual output of 335GWh has been estimated based on 80% utilisation
Mangahewa	50	
New Plymouth	0	'The plant is now mothballed following the discovery of asbestos in the plant earlier in 2007. The first of the station's five generating units was commissioned in 1974. It injected into the grid on two buses (110kv and 200kv, NPL1101 and NPL2201, 2 units and 1 unit respectively). The station's 198 metre chimney is one of the tallest in New Zealand and contains one million bricks, 16,400 tonnes of concrete and 1,200 tonnes of reinforcing steel. It is designed to sway between five and eight cm during 40 to 60 knot winds.
Otahuhu A	0	The first four units of Otahuhu A were commissioned in 1968. At the time it was the first large gas turbine power station in Australasia. Because of age and low thermal efficiency the plant is now only ever operated for emergency reasons. Two of the three available units are

		currently operated continuously to provide 'reactive power' for the electricity transmission system.
Otahuhu B	2380	Otahuhu B capacity varies with the source of the data. The 380 MW figure comes from Contact Energy's website. Transpower reserve modelling documentation lists OTAB's capacity at 395 MW. ACS data has capacity at 372 MW
Southdown	1400	Each of the turbines operates independently. This allows continued electricity production during maintenance or unplanned outages of one turbine. The construction of an expansion to Southdown was completed in 2007, taking the capacity to 175MW and production up to an estimated 1400 GWh per year.
Stratford Peaker	350	The two units are high efficiency LMS-100 gas turbine generators. Have assumed 20% utilisation to estimate GWh
TCC - Taranaki Combined Cycle	3350	Taranaki Combined Cycle was the first large-scale combined cycle gas turbine station to be built in New Zealand. Construction began in July 1996, with the plant completed in July 1998. The 367 megawatt station uses approximately 1.4 million cubic metres of natural gas per day in generation, and has an efficiency of around 55.5%. Capacity at the plant was increased from 367 to 385 MW during refurbishment in 2008.

Table 69. Natural Gas Cogeneration Stations [40]

Station Name	Typical Annual GWh	Notes
Auckland District Hospital	7	Built by Energy for Industry, Baseload heat: 4.2MW, electricity: 3.6MW net, standby power: 2.8MW
Bay Milk Edgecumbe	54	
Kapuni	111	The plant provides heat and power for local industry. Some 490,000 tonnes of steam a year is also produced for use in the NGC Kapuni Gas Treatment Plant. This steam allows NGC's Benfield plants to strip carbon dioxide from Kapuni gas to maintain pipeline specifications. Steam excess to NGC's needs is transported via a dedicated 3 km long steam line to Lactose New Zealand's dairy processing plant. Units : Gas: 2 at 10.3 MW, steam: 1 at 3.2MW, 1 at 1.5 MW. The plant has a rated output of 25 MW. Of this 20 MW is exported to the national grid.The plant is owned by Bay of Plenty Energy and NGC as a joint venture
Kawerau - TPP	271	
Kiwi Dairy, Hawera (Whareroa)	400	The Kiwi Cogeneration Station is located onsite at Fonterra's factory in Hawera, Taranaki and first entered production in 1996 as a gas-driven twin 10 MW turbine. A further two 10 MW turbines were later installed in conjunction with a 26 MW back pressure steam turbine. Gas is fed directly from the Kapuni production station, 22 kilometers, away via a dedicated pipeline. Note : Generation is metered at HWA1102 KIWI GG. For reconciliation

		generation is split equally between two buses HWA1102 TODD GG and HWA1102 MERI GG
Te Awamutu - Anchor Products	0	The generation plant was decommissioned in November 2007. The plant was based on a 54MW Pratt and Whitney aero-derivative Twinpak gas turbine exhausting into a heat recovery boiler to raise steam for process use. In normal operation only one of the two gas turbines of the Twinpak was in service, with the other available for backup in the case of an outage of the operating unit, or for operation as a peaking unit.
Te Rapa	200	The Te Rapa power station was commissioned in 1999 and is a cogeneration facility providing high quality steam and electricity to Fonterra's Te Rapa factory, one of the world's largest milk powder drying plants. Surplus electricity is directed back to the local area.
Wellington Hospital	0	Total annual injection into local network less than 0.1GWh per annum from CDS. Primarily used for backup. Consumption mainly internal to hospital when running. 4x Merriless-Blackstone 8cyl recip diesels with Brush Alternators 2.5MW rated, 2.0MW MCR

Appendix D.2: Kapuni Natural Gas Composition Before Processing

Table 70. Kapuni Before Processing Composition Data [48]

Kapuni Before Processing Composition	Mole Fraction (%)
CO_2	42.6
N_2	0.3
Methane	45.8
Ethane	5.5
Propane	3.5
Butanes	1.6
Pentanes	0.4
Hexanes and heavier	0.3

Appendix E: Geothermal

Appendix E.1: Geothermal Efficiency Results

Table 71. Geothermal Electricity Generation Energy and Exergy Efficiencies for Individual Power Stations

Region	Power Plant Name	Energy efficiency (%)	Exergy Efficiency (%)
Kawerau	Kawerau Geothermal	13	53
Kawerau	Kawerau KA24	14	51
Kawerau	Kawerau Binary - BoPE (TG1 and TG2)	5	28
Mokai	Mokai (general)	15	44
Ngatamariki	Ngatamariki	13	42
Ngawha	Ngawha	14	43
Ohaaki	Ohaaki Power Station	12	42
Rotokawa	Rotokawa	19	64
Rotokawa	Nga Awa Purua	16	56
Tauhara	Te Huka Binary Plant	10	37
Wairekei	Wairakei A and B and Binary	10	33
Wairakei	Te Mihi	12	36
Wairekei	Poihipi	16	57

Table 72. Geothermal Secondary Use Energy and Exergy Efficiencies

Region	Secondary Use Name	Energy efficiency (%)	Exergy Efficiency (%)
Kawerau	Kawerau Overall Secondary Use	15	23
Mokai	Mokai Glass House	50	8
Mokai	Miraka Whole Milk Powder Plant	60	1
Ohaaki	Ohaaki Thermal Kilns	20	61
Tauhara	Tenon Kilns	21	17
Wairekei	NETCOR Tourism Facility	66	4
Wairekei	Wairakei Prawn Farm	35	29
Wairekei	Wairakei Resort Hotel	94	0
	Overall	10.27	77.31

Table 73. Geothermal Direct Use Energy and Exergy Efficiencies by Sector

Sector	Energy Efficiency (%)	Exergy Efficiency (%)
Agricultural	52	75
Industrial	54	53
Commercial	43	67
Residential	69	71
Transport	0	0
Overall	42	75

Table 74. Geothermal Direct Use Energy and Exergy Efficiencies by End-Use Process

Direct Use Process	Energy Efficiency (%)	Exergy Efficiency (%)
Space Heating	39	71
Water Heating	45	80
Greenhouse Heating	59	71
Fish and Animal Farming	48	88
Industrial Process Heat	54	68
Bathing and Swimming	42	76
Other Uses	99	59
Residential space heating	40	71
Residential water heating	40	80
Overall	42	75

Table 75. Overall Geothermal Field Energy and Exergy Efficiencies

Geothermal Field	Energy Efficiency (%)	Exergy Efficiency (%)
Kawerau*	13	40
Mokai*	16	46
Ngatamariki	13	42
Nhawha	14	43
Ohaaki – Broadlands*	11	40
Rotokawa	16	57
Tauhara*	11	37
Wairakei*	10	34

Appendix F: Biomass and Biofuels

Appendix F.1: Biofuels Composition Data

Table 76. Biofuels calorific values [15]

Type of Wood	GCV (MJ/kg)	NCV (MJ/kg)
Oven-dried Wood	20.55	19.20
Fresh Harvested	9.33	7.40
Bark	9.06	7.00
Fuel Wood	12.08	10.30
Wooden Containers	14.94	13.30
Furniture Residues	17.79	16.30
Black Liquor	10.5	8.60

Appendix F.2: Biofuels Energy Supply and Use

Table 77. Biogas and woody biomass energy supply and use [15]

Calendar Year	Biogas				Woody biomass		
	Supply	*Use*			*Supply*	*Use*	
	Production	Electricity	Cogeneration	Direct Use	Production	Cogeneration	Direct Use[2]
1991	**2.06**	0.58	1.36	0.11	**39.02**	5.18	33.84
1992	**2.11**	0.64	1.36	0.11	**39.00**	5.18	33.81
1993	**2.11**	0.64	1.36	0.11	**41.15**	5.18	35.97
1994	**2.19**	0.64	1.45	0.11	**43.21**	5.18	38.03
1995	**2.32**	0.74	1.47	0.11	**44.44**	5.18	39.25

1996	**1.99**	0.86	1.01	0.11	**42.84**	4.78	38.06
1997	**1.91**	1.01	0.78	0.12	**44.94**	4.80	40.13
1998	**1.87**	0.84	0.91	0.12	**47.64**	6.24	41.40
1999	**1.68**	0.93	0.56	0.19	**52.95**	5.79	47.16
2000	**1.52**	0.92	0.40	0.20	**57.86**	6.59	51.27
2001	**1.53**	0.86	0.43	0.23	**57.10**	5.07	52.03
2002	**1.93**	0.98	0.71	0.24	**61.25**	3.25	58.00
2003	**2.51**	1.43	0.85	0.23	**61.42**	2.75	58.67
2004	**2.72**	1.71	0.85	0.16	**66.04**	3.43	62.61
2005	**2.75**	1.66	0.83	0.27	**65.70**	3.83	61.87
2006	**3.11**	1.87	0.93	0.31	**65.11**	4.15	60.95
2007	**3.08**	1.90	0.85	0.33	**62.27**	4.38	57.90
2008	**2.93**	1.79	0.81	0.33	**57.91**	4.53	53.38
2009	**3.09**	1.89	0.88	0.33	**53.41**	4.93	48.48
2010	**3.13**	1.96	0.84	0.33	**60.07**	5.08	54.99
2011	**3.34**	2.24	0.76	0.33	**60.76**	5.10	55.65
2012	**3.27**	2.19	0.74	0.33	**60.41**	5.07	55.34
2013	**3.20**	2.12	0.74	0.33	**57.32**	5.06	52.26
2014	**3.20**	2.12	0.74	0.33	**58.28**	5.06	53.22

Appendix G: Overall Results Appendix

Appendix G.1: Data for Overall Energy Sankey Diagram

Table 78. Data for overall energy Sankey diagram

		Delivered to:						
		Agricultural	Industrial	Commercial	Residential	Transport	Energy Product	Energy Conversion Loss
From	Transformation	9.8PJ	52.9 PJ	33.7 PJ	44.5 PJ	0.3 PJ	22.0 PJ	202.7 PJ
	End-Use	23.1 PJ	137.1 PJ	19.5 PJ	15.6 PJ	191.8 PJ		
	Agricultural						14.0 PJ	18.9 PJ
	Industrial						130.7 PJ	59.3 PJ
	Commercial						45.1 PJ	8.0 PJ
	Residential						44.4 PJ	15.7 PJ
	Transport						33.9 PJ	158.2 PJ

Appendix G.2. Overall Energy and Exergy Efficiencies

Table 79. Overall energy and exergy efficiencies for transformation and end-use sectors

	Energy Efficiency	Exergy Efficiency
Transformation	44	67
Agricultural	43	22
Industrial	69	34
Commercial	85	18
Residential	74	9
Transport	18	17

Appendix G.3: Data for Overall Exergy Sankey Diagram

Table 80. Data for overall exergy Sankey diagram

		Delivered to:						
		Agricultural	Industrial	Commercial	Residential	Transport	Exergy Product	Exergy Conversion Loss
From	Transformation	9.8 PJ	52.9 PJ	33.7 PJ	44.5 PJ	0.3 PJ	19.3 PJ	76.2 PJ
	End-Use	24.7 PJ	154.7 PJ	15.8 PJ	20.3 PJ	205.3 PJ		
	Agricultural						7.6 PJ	26.8 PJ
	Industrial						72.1 PJ	135.5 PJ
	Commercial						8.7 PJ	40.8 PJ
	Residential						6.1 PJ	58.8 PJ
	Transport						34.2 PJ	171.4 PJ

Appendix H: Discussion

Appendix H.1: The Impact of Geothermal Systems Results

Table 81. Total primary energy and exergy supply data

Resource	Energy Supply (PJ) [15]	Exergy Supply (PJ)
Coal	36	44
Oil	238	254
Gas	133	139
Geothermal	200	59
Biofuels/Biomass	52	69
Other Renewables	96	96

Appendix H.2: Waste and Losses Results

Table 82. Energy and exergy losses from each sector

Sector	Energy losses (PJ)	Exergy losses (PJ)
Transformation	203	76
Agricultural	19	27
Industrial	59	135
Commercial	8	41
Residential	16	59
Transportation	158	171
Total	463	509

Appendix H:3. Global Trends

Table 83. National energy and exergy efficiencies of countries

Country	Energy Efficiency (%)	Exergy Efficiency (%)
NZ (2014)	38	22
US (1970) [3]	51	21
Canada (1986) [5]	51	24
World (1990) [8]	39	15
OECD (1990) [8]	48	17
Turkey (1993) [12]	42	26
Saudi Arabia (1993) [13]	60	39
Saudi Arabia (2001) [13]	50	31
Japan (1985) [7]		21
Norway (1995) [9]		24
Italy (1990) [10]		18
Sweden (1980) [11]		20

Table 84. End-use sector exergy efficiencies for NZ and OECD

Exergy Efficiency	Agricultural	Industrial	Commercial	Residential	Transport	Total
New Zealand (2014)	22	35	18	9	17	17
OECD (1990) [8]		32	7	7	15	12

Appendix H:4. Productivity

Table 85. GPD per exergy input for New Zealand sectors

Sector	**Exergy input (PJ)**	**GDP (billion NZD)** [50]	**GDP/Exergy Input**
Agricultural	34.5	14	0.4
Industrial	207.6	47	0.2
Commercial	49.5	137	2.8
Residential	64.9	0	0.0
Transport	205.6	10	0.04

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